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The Application of Encapsulation Material Stability Data to Photovoltaic Module Life Assessment

C. D. Coulbert

April 1, 1983

Prepared for
U.S. Department of Energy
Through an Agreement with
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Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of cost-competitive solar arrays.

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ACKNOWLEDGEMENT

The author gratefully acknowledges the assistance and numerous contributions of members of the various Flat-Plate Solar Array Project technical groups. This report has attempted to provide an approach for integrating overall photovoltaic module stability and durability data with specific data on encapsulant material aging and degradation. It is expected that this cooperative integration effort will be a continuing one.

ABSTRACT

For any piece of hardware that degrades when subject to environmental and application stresses, the route or sequence that describes the degradation process may be summarized in terms of six key words: LOADS, RESPONSE, CHANGE, DAMAGE, FAILURE, and PENALTY. Applied to photovoltaic modules, these six factors form the core outline of an expanded failure analysis matrix for unifying and integrating relevant material degradation data and analyses. An important feature of this approach is the deliberate differentiation between factors such as CHANGE, DAMAGE, and FAILURE. The application of this outline to materials degradation research facilitates the distinction between quantifying material property changes and quantifying module damage or power loss with their economic consequences.

The approach recommended for relating material stability data to photovoltaic module life is to use the degree of DAMAGE to (1) optical coupling, (2) encapsulant package integrity, (3) PV circuit integrity or (4) electrical isolation as the quantitative criterion for assessing module potential service life rather than simply using module power loss.

The failure analysis matrix and its application to module life assessment, with specific examples and data, are described.

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SECTION I

INTRODUCTION

This report describes an approach to assessing photovoltaic (PV) module life based on the durability of the encapsulant material systems. Since there may be several competing modes of PV module failure, this report also discusses the status of characterizing other potential life-limiting damage mechanisms, such as hail damage and interconnect fatigue. The emphasis in this report is on assessing the effects of encapsulant material aging and consequent changes in encapsulant material properties when PV modules are exposed to environmental and application loads during field deployment.

The severity and degrading effects of a number of specific environmental and application loads have been investigated and reported through Flat-Plate Solar Array Project (FSA) contractors' reports and Jet Propulsion Laboratory (JPL)-published reports. Some of the subject areas covered in these reports are:

(1) Soiling. The characteristics and rate of accumulation of airborne dirt and pollutants on various PV module surfaces as a function of location, time, and surface treatment, experimental and theoretical treatment of causes, and control (References 1 through 5).

(2) Hail. The probable geographical distribution of hailstone sizes and frequencies and the responses of different PV module designs to hail damage during field and laboratory tests (References 6 through 9).

(3) Wind. Intensities, effects of PV array design on panel wind loads, and design guidelines for PV module durability (References 6, 10, and 11).

(4) Interconnect Fatigue. Field experience, design analysis, laboratory testing and design criteria (References 12, 13).

(5) Photothermal Degradation. Photodegradation of polymers; mechanisms, rates and physical and chemical changes (References 14 through 19).

(6) Cell cracking. Field and test experience, cell-strength characteristics and consequences of cell cracking and damage-tolerant designs (References 20 through 23).

(7) Electrical Isolation. Statistical dielectric characteristics of polymer films and film combinations, test techniques and results (References 24 and 25).

There is no single sequence of tests or analyses presently available that may be applied to a PV module to predict its potential life or failure probability. There are tests and guidelines available in the references cited above for eliminating or controlling specific failure modes and life-limiting degradation mechanisms. Additional data and experience are accumulating to identify specific problem areas related to module design, material selection and quality control. Confidence is growing in the probability of well-designed PV modules being able to operate reliably for 20 years or longer.

One of the goals of this report is to provide a framework or basis for unifying and integrating available PV module degradation data using classical statistics and reliability analysis methods. The development of this proposed approach to integrating life-assessment technology and a presentation of application examples constitute the body of this report.

SECTION II

MODULE FAILURE ANALYSIS MATRIX

A. THE MATRIX OUTLINE

For any given piece of hardware (from light bulb to automobile) that degrades when subject to environmental and application stresses, the route or sequence that describes the degradation process may be summarized in terms of six key words: LOADS, RESPONSE, CHANGE, DAMAGE, FAILURE, and PENALTY (Figure 1). In application to PV modules, this core outline is expanded as in Figure 2 to include all parameters relevant to characterizing the loads, responses and degradation mechanisms that influence module life and failure probability. The expanded outline thus becomes a failure analysis matrix of all of the different environmental and application loads, the module components, their individual and combined responses, and possible interactions.

With appropriate definitions of the elements of this failure analysis matrix, which are given in Section III, a framework or outline is available for classifying, correlating and comparing the various pieces of degradation data being generated for PV modules, components and materials.

An important feature of this approach is the deliberate differentiation between factors such as CHANGE, DAMAGE and FAILURE. It is recognized that encapsulant properties may CHANGE with time without a significant change in module performance. Furthermore, changes that may be classified as DAMAGE (such as cracked cells) may be prevented from becoming FAILURES by the

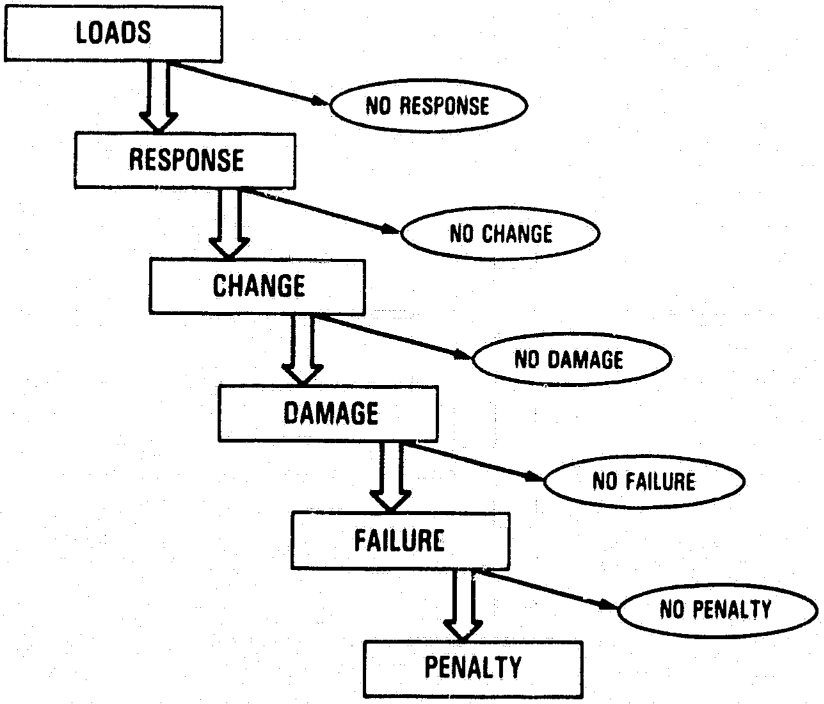

Figure 1. Typical Durability Assessment Sequence

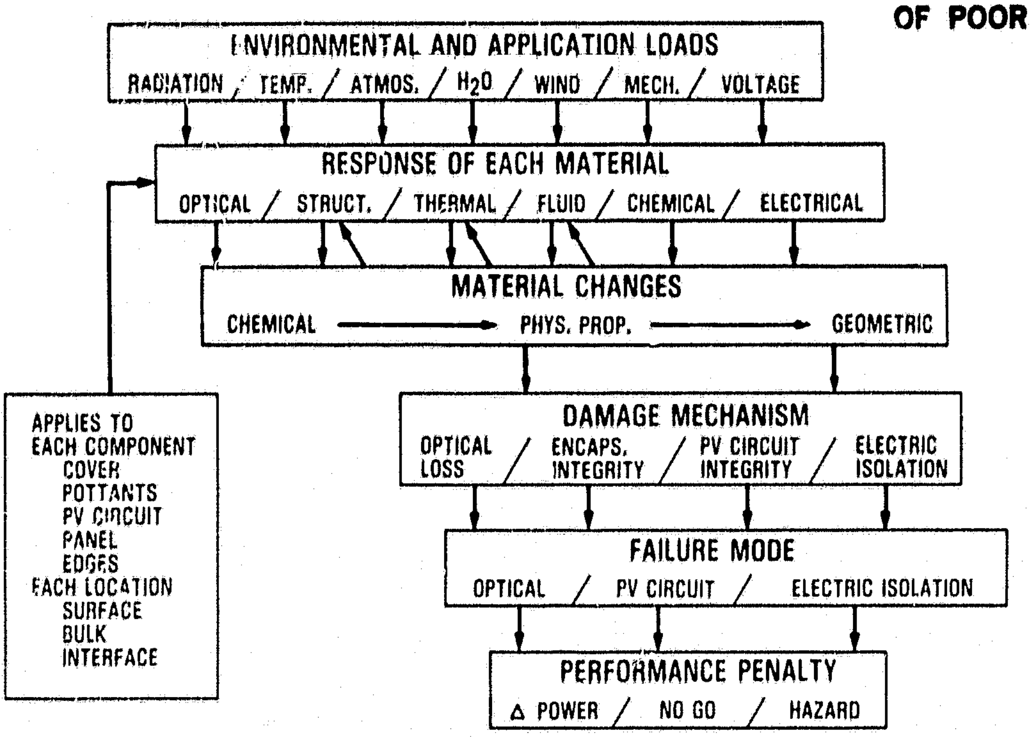

Figure 2. PV Module Failure-Analysis Matrix

incorporation of damage-tolerant design features such as redundant cell interconnects and bypass diodes.

Another feature of this proposed failure analysis outline is its accommodation of time-related and statistically distributed degradation effects. Each step in the core outline in Figure 1 may be related to the following step by an appropriate time function or a statistical or probability relationship. For instance, the PV module response to environmental temperature and solar radiation LOADS would be a temperature rise and thermal expansion as a function of time (short-term). The polymeric encapsulant material absorbing part of the solar radiation may consequently experience a slow (long-term) CHANGE in chemical and physical properties (photolysis) as a function of time under the imposed LOADS. Simultaneously, the different thermal expansion RESPONSES of the module components may cause solar-cell or interconnect stresses, resulting in an increased DAMAGE or FAILURE probability. Conceptually, each of these CHANGE and DAMAGE functional relationships could be quantified and experimentally verified.

Referring again to Figure 1 and to the boxes labeled CHANGE, NO DAMAGE and DAMAGE, one may picture a situation in which a component's or material's initial property (such as dielectric strength) may result in a quantitative statistical distribution of observed effects, (i.e., failure probability) between NO DAMAGE and DAMAGE (e.g., voltage breakdown). With time, a shift in the statistical or probability distribution of the DAMAGE/NO DAMAGE effects may occur due to a quantitative CHANGE in material properties due to aging effects or cyclic loading effects.

Because of the readily apparent complexity of attempting to characterize and quantify all of the degradation relationships and interactions implied by this failure analysis matrix, the initial value of this outline may be mainly in the following areas:

(1) A checklist of failure factors, sequences, and potential interactions.

(2) An outline or framework for developing a test plan, assuring its completeness, and defining its limitations.

(3) A framework for describing and classifying available test results in scope, sequence, and completeness.

(4) A framework for compiling and integrating the general data base of material properties and material degradation technology that is available.

The application of this approach to polymer material degradation research will facilitate the distinction between quantifying material property CHANGES and quantifying the resulting module power loss (PENALTY) and economic consequences. One is also encouraged by this outline to face the question (or fill the void) of how a specific material property CHANGE such as decreased pottant modulus, or a visible DAMAGE occurrence such as delamination, may result in reduced module life or array performance.

B. DEFINITIONS FOR THE FAILURE ANALYSIS MATRIX

To facilitate the use of this outline or matrix in organizing failure-analysis and life-assessment activities, distinctive definitions of the matrix elements in Figure 2 are presented. In the definitions to follow, it may appear that some load or response effect has been omitted from consideration. It probably has, and the reader is invited to insert the missing elements. It is a basic assumption and goal of this outline development that all possible parameters of hardware description, environmental and application loads, material and component responses and degradation effects be included within the matrix elements shown in Figure 2. The following definitions are set forth to provide a consistent basis for comparing and combining different degradation effects, differentiating material RESPONSE from CHANGE and DAMAGE, and differentiating between DAMAGE and FAILURE. In practice, all of these steps may occur simultaneously (e.g., a lighted match in a gasoline tank!), but conceptually each effect may be defined separately. These distinctions are especially relevant in separating encapsulant material degradation (aging) effects from the operational degradation of the PV circuit.

A definition with examples for each of the six key outline headings is presented in the following text.

1. LOADS, Environmental and Application

When the PV module is deployed at a specific array site, it is subjected to a variety of environmental and application LOADS and hazards that may be identified and quantified for each site and array application.

These LOADS include solar radiation, ambient temperature, atmospheric gaseous and solid constituents, moisture in all its various forms (including hail), winds, mechanical/physical factors (including manufacturing flaws, transportation and storage, mounting forces, washing, shadowing, vandalism, birds and animals, etc.), loads induced by array voltages and current flows, lightning, earthquakes, and accidental fires. A vast collection of data exists on the quantity, intensity, time distribution, and probability of occurrence for most of these environmental LOAD parameters for many specific geographic locations. In collecting and documenting such data for failure prediction, it must be determined which characteristics of the load parameters are most relevant; i.e., averages, extremes, frequencies, intensities, or cumulative values. This must be determined from experience and by assessing experimentally and analytically the response of each module component.

2. RESPONSE, Each Material and Component

When deployed, each module material or component will exhibit a RESPONSE (which may be reversible or non-reversible) to each of the LOADS noted above, which may result in a CHANGE or NO CHANGE in the materials. Components or individual materials completely isolated or decoupled from a specific environmental parameter may be classified as NO RESPONSE. What are usually called material properties, such as thermal expansion coefficient and elastic modulus, are RESPONSE coefficients or proportionality constants relating material response to applied LOADS (Figure 3). Also, the PV circuit I-V curve is the normal RESPONSE to the solar radiation LOAD including the effect of ambient temperature. The evaluation of RESPONSES applies to each module component individually, such as covers, pottants, PV circuitry, structural panel, edge seal, and frame (as well as their combinations), and also to each location within the component such as surface, bulk, or interface.

Responses of each material may also be classified as active or passive. An example of a passive response would be the spectral transmission by module covers of the total incident solar radiation, while an active response would be the temperature rise and expansion of a component and the chemical reactions associated with absorbed ultraviolet light (UV) in specific wavelength regions.

Recycle loops and response interactions are also recognized as analysis requirements. Damage or property changes in one material may cause a change in response of another material or component, requiring a recycle loop in the analysis.

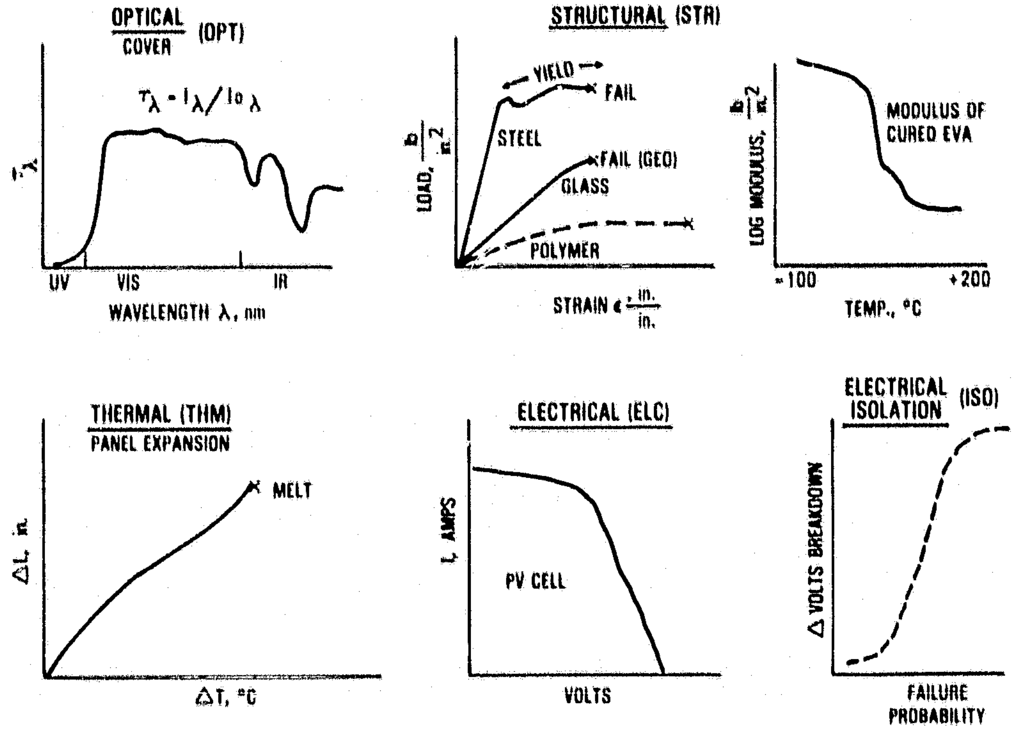

Figure 3. Quantifying Response and Limits for Short-time Loads

3. CHANGE, Chemical, Physical, and Geometric

CHANGE is defined as a non-reversible RESPONSE to LOADS and includes chemical changes that could result in changes in physical properties as well as geometric changes such as shrinkage. Some CHANGES may be allowable and benign (NO DAMAGE) while others would be classed as DAMAGE affecting optical coupling, encapsulant package integrity, PV circuit integrity, or electrical isolation.

Material CHANGE experienced may also be classified as to where it occurs; i.e., a surface condition, a bulk property, an interface bond strength, stress, or reaction. Delamination is an interface loss of bond integrity due to interface stresses exceeding interface bond strengths. Interface stresses may vary with thermal and structural loads while bond strength may vary with processing conditions, temperature, time and environmental moisture. Interface chemistry and UV absorption may also be relevant.

Of major interest in this analysis step are those changes in material properties, material configuration (geometry), or material condition (e.g., abrasion, crazing) that may alter the subsequent response of the material or component to its relevant load. For instance, if UV absorption in the pottant causes it to embrittle (increased modulus or reduced elongation) with exposure time, the bending and tensile stresses experienced by the silicon-wafer solar cells could increase during module flexing and temperature cycling, which would in turn increase the probability of cell cracking. While the response of a whole encapsulated silicon cell to moisture and to voltage bias may be negligible, the presence of a cell crack, even with redundant interconnects, may result in the reduction of local shunt resistance due to moisture accumulation in the cell crack. This phenomenon has been observed experimentally but needs more work in characterization.

Measurements on a variety of changes in material properties such as modulus, spectral transmission, weight loss, and strength have been made as a function of exposure time over a range of temperatures, UV intensity and oxygen access (Reference 19). Based on these data, statements can be made about their relative photothermal stability. The relationships between these observed property changes and the prediction of a probable PV circuit failure mode and time of occurrence under field-exposure conditions have yet to be determined adequately to forecast module service life.

An analytical model of the chemistry of photodegration changes in EVA is being developed under FSA contract by the University of Toronto (Reference 18). With satisfactory completion of this computer model and appropriate experimental test data, curves of property changes versus exposure time, configuration and temperature will be available for EVA (and subsequently other polymers) to be used in durability assessment studies.

The current design approach is to try to select materials, design configurations, and module operating conditions that would result in negligible or benign property changes in 20 years.

4. DAMAGE, Loss of Integrity

The basic performance requirements of a PV module encapsulation system as shown schematically in Figure 4 are to provide optical coupling, structural support, electrical isolation and protection of PV circuit integrity. For a module material CHANGE (either physical or geometric) to be classed as DAMAGE in the context of this matrix outline, it must affect the module quality (not necessarily module power) in one or more of the four following aspects:

(1) Loss of optical coupling (transmission) between the active solar cell surface and incident solar radiation.

(2) Loss of encapsulation package physical integrity (cover split, delamination, etc.).

(3) Loss of PV circuit physical integrity or electrical performance.

(4) Loss of electrical isolation between the active PV circuit and ground, or development of a shock hazard as manifested by shorting, arcing, excessive leakage current or an exposed conductor.

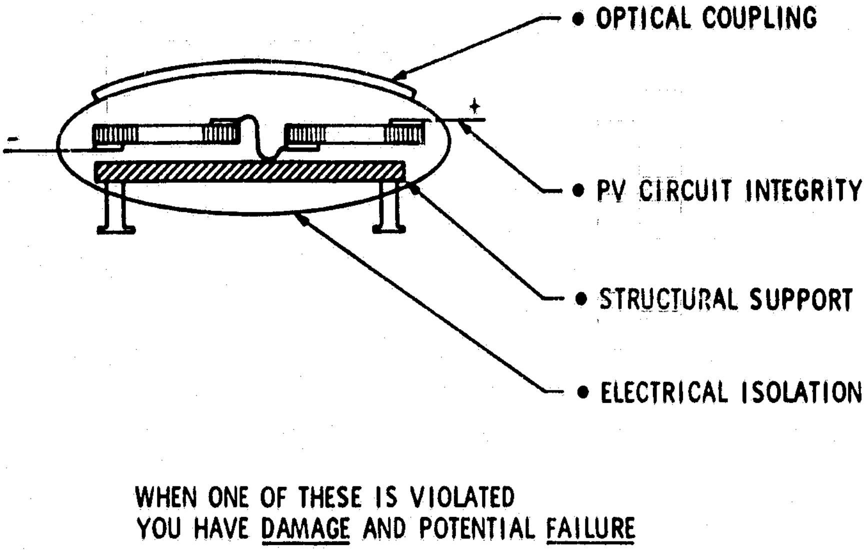

Figure 4. Requirements for Encapsulation

a. Optical Coupling. The damage mechanisms related to optical coupling include soil retention, effect of natural and deliberate surface cleaning actions, surface abrasion, delaminations over cells, pottant or cover turning yellow or clouding, or deterioration of antireflection coatings. Some time-related and site-related data are available on soiling phenomena, which have been used mainly for material and process selection. With the adoption of recommended module designs and materials, it will be necessary to characterize the long-term optical coupling degradation due to all causes, because this is one of the most cost/performance-sensitive design parameters affecting the economics of solar energy.

b. Encapsulant Integrity. Damage to the integrity of the encapsulation package due to module cover or pottant cracking, splitting, delaminating, or peeling is a visible damage mechanism. However, this has not always resulted in an immediate loss of module performance. The expected deteriorating effect would be the access of water to the PV circuit and the consequent actions of corrosion, shorting, swelling, freezing, or chemical reactions. Data establishing the relationships between encapsulant damage and module performance is very limited. The current design approach is to consider such damage mechanisms as unallowable and to design for no loss of encapsulant integrity. However, it is expected that after a long field exposure time to UV, moisture, and temperature cycling of low-cost module designs containing polymeric materials and lower-cost metals, damage will eventually occur to the encapsulant package. This damage, in turn, could allow other PV circuit damage mechanisms, such as fatigue or corrosion, to become life-limiting failure modes.

c. PV Circuit Integrity. The heart of the solar-cell module is, of course, the PV circuit with its silicon cells, interconnects, and terminations. The basic design requirements for the encapsulation system are protection and mechanical support for the PV circuit components, maximum optical coupling to the solar input, and electrical insulation and isolation of the PV circuit from its surroundings. The PV circuit performance itself may degrade by several mechanisms:

(1) Loss of active cell area due to cell cracking.

(2) Loss of power due to series cell mismatching.

(3) Cell shadowing due to foreign objects or deposits on one or more cells.

(4) Degradation of the metallization-cell interface bond and ohmic contact.

(5) Increase in cell series resistance by metallization corrosion action.

(6) Decrease in cell shunt resistance by ion migration over the cell surface or edges under the influence of voltage or current flows.

(7) Cracked cells providing the opportunity for formation of a current shunt path between front and back of cell.

(8) Hot-spot heating damage due to cell back-bias heat dissipation.

Some of these effects on the PV circuit power output can be assessed analytically and experimentally. A much broader data base than that now available is needed to characterize these relationships completely for different cell materials, types and circuit designs.

Whether DAMAGE becomes a module FAILURE mode depends also on the fault-tolerant design features of the PV circuit. These features may include multiple cell interconnects, metallization pattern design, and series/parallel connection of solar cells.

d. Electrical Isolation. Electrical isolation damage may be primarily a safety consideration on a go/no-go basis. Data are required on the probability of electrical breakdown at specified voltages (1000-3000 volts) for various insulation configurations and material combinations and the degrading effects of long-term environmental exposure.

The significance of module leakage current at the microampere level and the adequacy of present qualification test standards are still under study. The effect of changes in leakage current due to aging also needs more study.

5. FAILURE, Module Performance Loss

FAILURE is defined as a permanent (irreversible) degradation in PV module performance in terms of solar-energy conversion efficiency and safety (aesthetics may also be a factor in some applications). Failure is usually construed as a performance decrement great enough to require repair or replacement of the item in service. In practice, the time of replacement (if done at all) would depend on the economics and statistics of the situation.

Failures generally fall into three categories with several possible damage mechanisms in each category as indicated in Figure 5. A brief definition or description of each failure type follows:

a. Infant Mortality. Module failures at normal exposure and use conditions due to module flaws introduced into the hardware during manufacture and not detected by applicable inspections and acceptance tests. This assumes that the module design has been qualified by test and analyses to withstand the normal exposure and use conditions with a reasonable margin of safety.

b. Random Flaw/Stress Failures. The statistical distribution of failures attributed to the combination or probable occurrence of inherent material flaws or localized design weaknesses interacting with statisically distributed applied excessive (but probable) loads. The excessive random loads may include hail, wind, temperature extremes, and human or animal activities.

c. Wearout Failures. These are module failures due to material aging, wear, corrosion, fatigue, and damage accumulation. Because of the wide variability and spatial distribution of material properties and stress levels, distinction between random and wearout module failures will depend on careful analyses of the failure mechanisms involved. Wearout failure assumes some nonreversible prefailure change in the internal characteristics of the module or module material due to application loading.

Experience with failures of encapsulated PV modules and with most other types of hardware leads to the expectation of a "bathtub" failure-rate-versus-time curve. Such a bathtub curve is in concept the superposition of

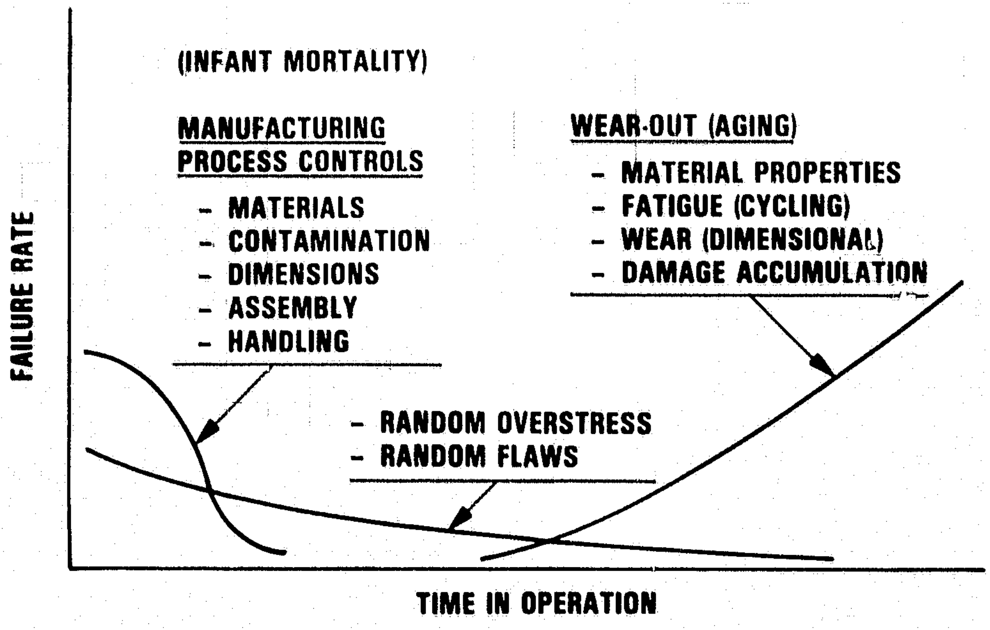

Figure 5. Module Failure-Rate Classification

the three curves or failure rates (Figure 5), consisting first of infant mortality failures, which should decrease with time as the faulty units are eliminated. The level portion of the failure-rate curve describes the random failure rate during the useful life of the hardware and is characterized by its reliability rating or mean time between failures (MTBF). As time continues, failure rates would be expected to increase because of wear-out and material-aging effects.

In the PV module, all of these failures are expected to fall into one of three areas:

(1) Loss of optical coupling or loss of radiant power transmitted to the solar cells (OPT).

(2) Loss of power conversion ability due to PV circuit damage (PVC).

(3) Loss of electrical isolation of the PV circuit, resulting in a short to ground or creation of a safety hazard (ISO).

6. PENALTY, Value Loss or Consequences

The PENALTY or consequences to array performance with a specific module failure mode (i.e., power loss, open or short circuit, or safety hazard) depends on complex factors including economics, array application, social perceptions, state of the art, alternative energy sources, etc. Discussions and an approach to evaluating life-cycle energy costs for various module failure modes and replacement strategies are presented in References 21, 26, 27 and 28.

SECTION III

APPLICATION OF THE FAILURE ANALYSIS MATRIX

A. REVIEWING AVAILABLE TEST RESULTS

A perusal of the failure analysis matrix of Figure 2 gives some indication of the possible complexity of following and quantifying the numerous PV module-degradation processes and sequences that may occur when a module is subjected to stresses and reactions caused by either field exposure or accelerated laboratory testing. In the development of test methods and design analysis techniques for assessing the long-term durability of PV modules, a variety of technical approaches have been pursued by FSA. Two diverse approaches currently used in characterizing material and component degradation phenomena are (1) field-site deployment of commercial PV modules at various locations (References 29 through 32), which may be contrasted with (2), laboratory testing of polymer pottants using nanosecond flash photolysis (Reference 33) to evaluate photoreaction kinetics. The purpose of each of these tests, as well as all other real-time and accelerated field and laboratory testing of modules and materials, is to provide data to fill at least three technical needs:

(1) An assessment of the stability, durability, and life potential of current PV module designs and hardware.

(2) Material selection and design criteria for improved performance of material systems and hardware.

(3) Development of valid tests, diagnostics and standards for evaluating and assuring the quality and durability of future PV modules.

Thus one application of the failure analysis matrix of Figure 2 is as a checklist of LOADS, RESPONSES, and CHANGES, and potential interactions among them, which must be included and considered in both failure analysis and test program planning. In the analysis and correlation of test data from the two diverse types of testing cited, the same failure analysis matrix would be applied but with differing levels of detail.

In field testing, the key test results are usually identified as FAILURE mode or loss of performance versus exposure time. These results may be correlated as a function of module design, general application and site LOAD parameters (e.g. hailstorms).

As a first-cut global correlation, one may plot failure rate or damage versus time for a particular module type at a specific site as in Figures 6 and 7. Such a plot identifies the short-term overall module reliability and the magnitude of the durability problem, but does not provide a rational basis for predicting future failure rates. With reference to applying the failure analysis matrix (Figure 2), it may be used in the analysis of failed modules to help identify, classify and localize the DAMAGE mechanism and, where possible, characterize material CHANGES that have occurred. These data then provide some criteria for design or material improvements, but still not a

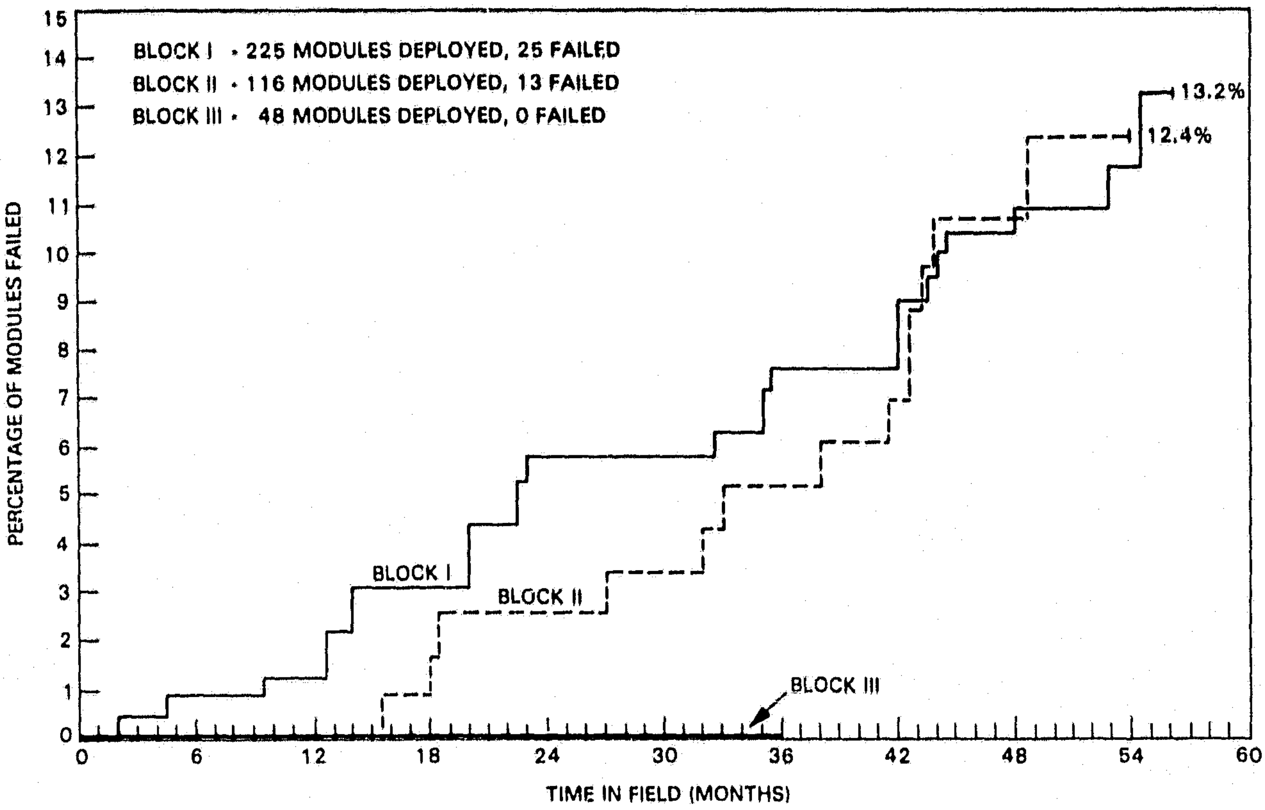

Figure 6. Summary of Photovoltaic Module Failures During JPL Field Testing, 1976-1981 (Failure is >25% Loss of Power)

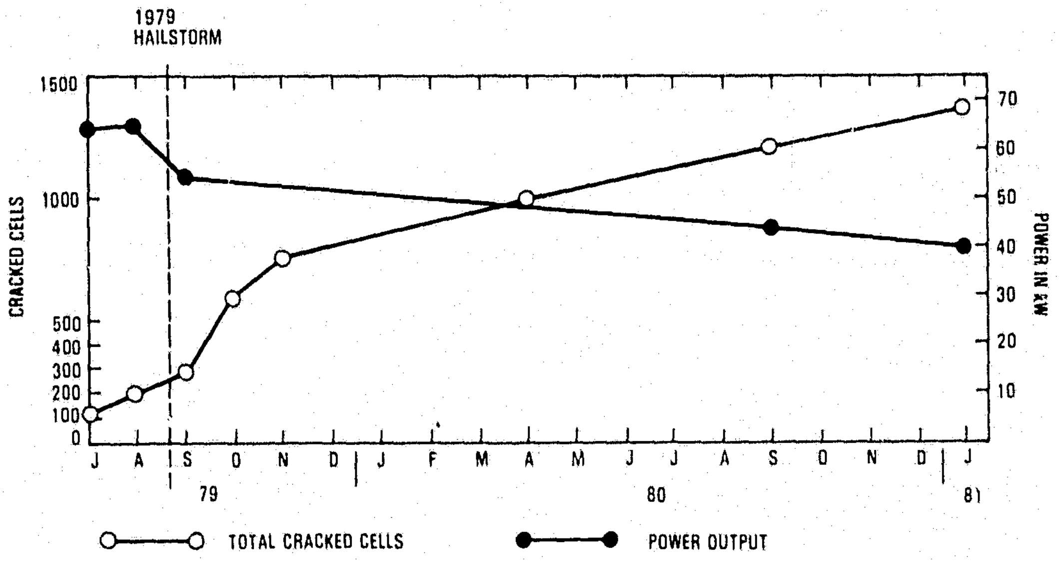

Figure 7. Module-Array Power Loss and Incidence of Cracked Cells versus Field Exposure Time

basis for life prediction. The complexity of predicting module DAMAGE based on material CHANGE is obvious as one considers the possible combinations of LOADS and RESPONSES involved in the degrading changes in each module component. Research in FSA has attempted to identify the more critical LOADS and CHANGES, and their time relationships. The effect of material CHANGE on module DAMAGE depends on relating the value of an encapsulant physical property to the probability of a failure mode or performance decrement.

The evolving approach within FSA to the assessment of durability or life potential of a photovoltaic module is based on experience and evaluations in three areas of module characterization:

(1) Identification and compilation of life-limiting module-damage mechanisms (Problem/Failure Reports).

(2) Evaluation of module-failure probability associated with specific damage mechanisms or material property and configuration (e.g., cell cracks).

(3) Characterization of material stability and rates of material degradation or rates of measurable property change as a function of time and combined environmental LOADS.

Two encapsulant-material property CHANGES due to aging which can directly and measurably affect PV module performance are encapsulant optical transmission and dielectric strength. Other encapsulant changes and damage such as pottant delamination, cover film splitting, polymer elastic modulus change, or superstrate glass sheet cracking have been observed but have not always resulted in an immediate or consistent loss in module power or in the development of an obvious safety hazard. The development of quantitative relationships between these forms of damage and loss of module power remains elusive. Therefore, the approach to designing for long-term module durability has been to eliminate or minimize the occurrence of these visible encapsulant damage mechanisms during the expected module service life. Quantifying long-term module performance losses resulting from such damage to the encapsulant remains to be evaluated from real-time field experience.

For instance, module damage such as broken interconnects, cracked cells, and delaminations have often been detected in modules without any indication of reduced module power. Such a module would be said to have a fault-tolerant design. In other modules, depending on the module design, such damage has resulted in sharply reduced power or complete module failure.

The great value of module durability field testing and qualification testing in the early stages of technology development has been to identify design faults and provide guidelines to module designers and manufacturers for the fabrication of higher-quality hardware incorporating fault-tolerant design features. This has greatly reduced the infant-mortality failure rates for current commercial PV modules, and has increased their life expectancy.

Module damage mechanisms and processes observed and identified during qualification and field testing that may or may not have degraded module performance, limited module life, or required module replacement for safety reasons include:

(1) Module surface soiling, reversible and non-reversible.

(2) Solar-cell cracking due to pre-existing cell-edge flaws and stressing by various mechanical and thermal loads.

(3) Interconnect failures due to thermal-cycle fatigue fractures or disbonds between the interconnect and cell surface. Disbonds due to solder melting have been observed.

(4) Structural failure of glass-sheet superstrates due to mechanical mounting forces, thermally induced loads and hail or other impact. Glass failure due to wind forces alone have not been reported.

(5) Electrical isolation breakdown at 1500 volts or less has been observed and attributed mainly to manufacturing flaws such as metal projections and sharp edges, voids, contamination, mislocated cells and conducting metal components.

(6) Excess leakage current ($>50\ \mu A$) through the encapsulant to ground at 1500 V, particularly during salt-fog exposures.

(7) Visible deterioration of electrical termination hardware, both metal conductors and insulating polymers.

(8) Degradation of the physical/chemical properties of polymeric encapsulants as manifested by color change, shrinkage, splits and cracks, embrittlement, softening, surface tackiness, or bubble formation.

(9) Delamination of encapsulant layers from cells and substrates producing visible interface voids.

(10) Corrosion of module and array structural hardware and fasteners exposed to atmosphere and corrosion of solar-cell circuit components within the module due to the combined effects of an electrical field and electrolytes formed by contaminants and intrusive moisture. Contaminants may come from the environment (SO_2) from manufacturing (solder flux), or polymer degradation reactions (acetic acid).

(11) Wrinkling and blistering of polymer film and aluminum foils used as back covers, due to thermal distortion and yielding during temperature and humidity cycling.

B. HOT-SPOT HEATING

Note that hot-spot heating is not listed above as a failure mechanism; it is the normal response of a solar cell module to several fault conditions, which leads to cell reverse bias. Fault conditions include cracked or mismatched cells, open-circuit interconnect failures, or non-uniform illumination (partial shadowing). Under these conditions the back-biased cell(s) may dissipate power equal to the product of the current and the reversed voltage that develops across the cell(s). Depending on the cell characteristics, the circuit design and the thermal characteristics of the encapsulant, the cell(s) may be heated to an elevated temperature sufficient to melt solder and cause gas evolution from the pottant, electrical isolation breakdown, cracked cells, and even fire.

Control of hot-spot heating and testing for resistance to damage by hot-spot heating is covered in FSA reports prepared by the FSA Engineering Sciences Area (e.g., References 34 and 35).

It is an objective of the Environmental Isolation Task to define the consequences of localized hot-spot heating and the effect on the long-term stability of the polymeric pottant candidates. The possible effects on pottant properties to be defined as a function of temperature and time include color change, gas (bubble) evolution, modulus change (softening or embrittlement), shrinkage or swelling, and loss of dielectric properties.

The status of developing quantitative time relationships between environmental exposure loads and module performance due to loss in optical coupling is presented in the following section. The effect on module performance, failure probability and safety due to aging changes in the dielectric characteristics of the encapsulant package is under investigation.

C. USE OF THE MATRIX AS AN ORGANIZING AID

To facilitate the use of the failure analysis matrix of Figure 2 in organizing failure analysis and life assessment activities, it has been rearranged in an alternative format, as shown in Figure 8, with three-letter symbols representing each element of the overall outline. The symbols used are defined in Appendix A. This format breaks the matrix outline down into its separate elements and parameters and displays them alongside their appropriate failure sequence steps, omitting the boxes and arrows. For planning and organizing specific tests or outlining the scope of a published set of test results, the chart may be visualized with blank spaces, as in Figure 9, to be filled in with the specific test parameters and sequences that are applicable as shown in the example of Figure 10. This example test plan describes a specific hardware design, loads imposed, responses monitored, and the progression of changes, damage and failures observed. The actual test program is described in Reference 36.

A cross comparison of the category chart of Figure 8 with the example test plan reveals which LOADS were not imposed (e.g., no radiation), which RESPONSES were tracked and where the critical DAMAGE occurred. A thermal (THM) RESPONSE interaction is indicated between the substrate panel (PAN) and the PV circuit (PVC). The FAILURE was in the PV circuit interconnects, even though redundant interconnects were used. These test results confirmed and were consistent with the results of the JPL interconnect fatigue experimental and analytical studies reported in Reference 13.

The cell interconnect-fatigue problem is one of the best examples of a life-limiting module failure mode for which all the failure analysis sequence steps from LOAD to PENALTY have been quantified. As a result, design

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DESIGN DETAILS			HARDWARE DESCRIPTION						CONF, MTL & FLAWS
EXPOSURE	QUAL		FIELD	ACCEL / TIME					TEST CONDITIONS
LOADS	RAD	TMP	ATM	H2O	WND	MEC	VLT		INTENSITY/TIME
COMPONENT	COV	POT	PAN	EDG	PVC				OR MATERIALS
LOCALITY	SRF	BLK	INT						WHICH OR WHERE
RESPONSE	OPT	STR	THM	FLD	CHM	ELC			QUANTITATIVE
CHANGE	CHM	PHY	GEO						MEASURABLE/VISIBLE
DAMAGE	OPT	ENC	PVC	ISO					INTEGRITY VIOLATED
FAILURE	OPT	PVC	ISO						OPERATIONAL
PENALTY	PWR	NOG	HZD						VALUE LOSS

Figure 8. Durability-Analysis Plan Categories

principles and test standards have been formulated to control or eliminate interconnect fatigue as a life-limiting failure mode.

Two other FAILURE modes for which it appears that quantitative end-to-end failure analyses can be developed are optical loss and electrical isolation breakdown. These damage mechanisms are identified because they may occur within a single material and produce module failure without degradation of the other components in the PV circuit. As noted above, the task of

DESIGN DETAILS								
EXPOSURE								
LOADS								
COMPONENT								
LOCALITY								
RESPONSE								
CHANGE								
DAMAGE								
FAILURE								
PENALTY								

Figure 9. Durability-Analysis Planning Form

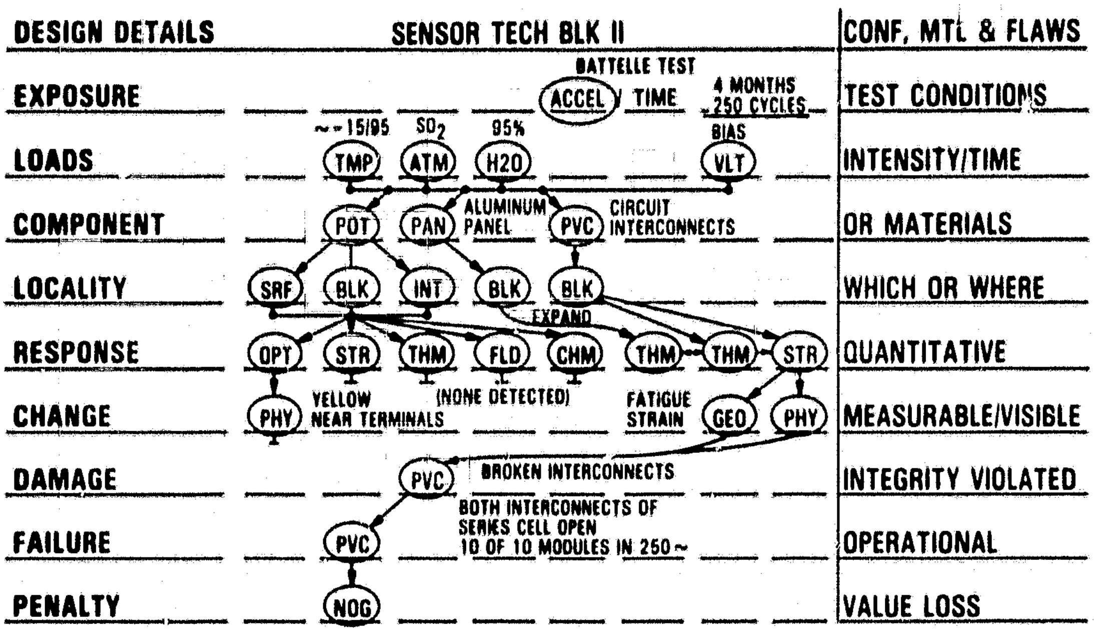

Figure 10. Durability-Analysis Example

quantifying the degradation rate of the PV circuit as a consequence of changes in encapsulant properties and possible interactions between the circuit and encapsulants is complex in the extreme.

Within FSA, the Engineering Sciences and Environmental Isolation groups are conducting tests (field and laboratory) to compile data and quantitative relationships for correlating and predicting both optical and electrical isolation degradation as a function of design, materials, loads, and time of exposure. The optical testing is described in the next section.

D. MODULE PERFORMANCE LOSSES VERSUS OPTICAL COUPLING

1. The General Problem

A graphic summary of a current FSA investigation of polymer optical degradation due to photothermal aging is presented in a matrix format in Figure 11. This outline shows two different test material configurations being used to monitor and validate an optical-loss mechanism and consequent PV module degradation rates under accelerated test conditions. In the one case, the spectral transmission changes in the polymer are measured separately and integrated analytically to calculate the expected change in module power. In the second case, the same material is tested as a solar-cell pottant with the cell power loss being measured directly. Of course, the cell power loss includes the combined effect of any other encapsulant or PV circuit damage along with the loss in optical coupling.

In the more general case, a loss in optical coupling includes many mechanisms that must be evaluated. Optical coupling is a broad term to encompass all optical phenomena that relate to the fraction of solar radiation energy incident upon a module cover surface that is finally absorbed by the

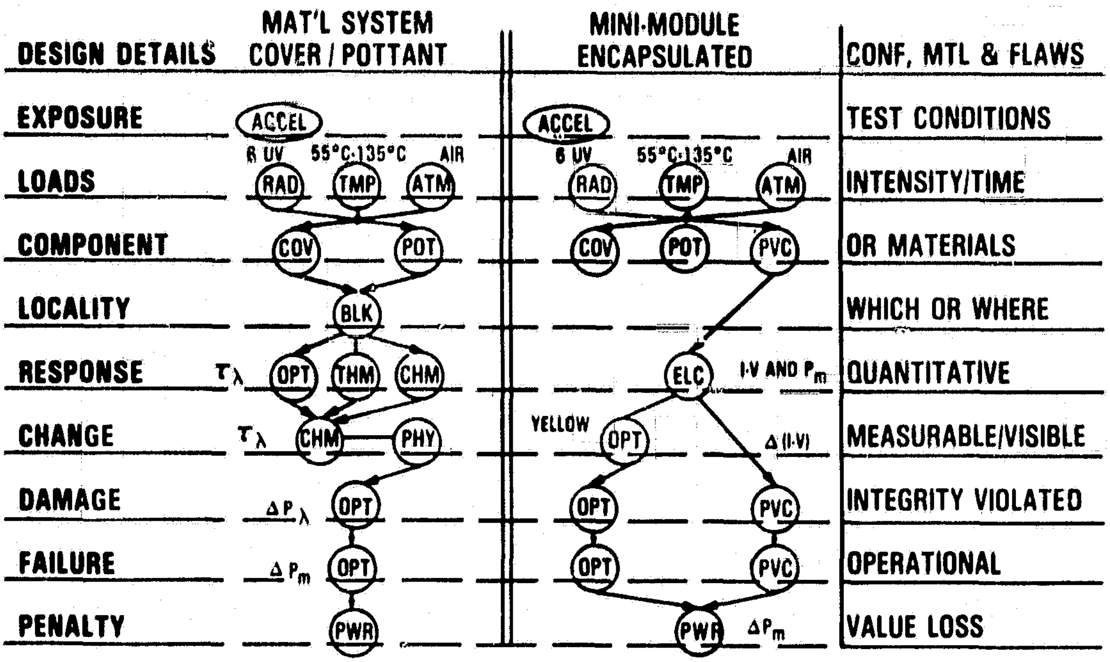

Figure 11. Optical-Durability Test Plans

solar cell to produce electricity. The factors that affect optical coupling include module orientation, surface soiling, surface roughness (abrasion or crazing), cover absorption (yellowing), delamination, bubbles, antireflection-coating damage, solar-cell surface texture, surface and interface reflectivity, and internal scattering. Most of these factors will vary with time of exposure and severity of the environmental loads.

The two optical coupling degradation factors shown by experience to be most prevalent and critical are surface soiling and polymer cover or pottant yellowing.

2. Soiling

Cover soiling, its causes, effects, and control are discussed in References 1 through 5. The typical characteristics of soiling, such as loss of power, rate of build-up, the effect of rain and the responses of different cover surfaces, are shown in Figures 12, 13, and 14. In an industrial atmosphere, power loss may exceed 25% to 30% in less than two months. The effect of surface treatments to reduce soil retention is also shown in Figures 13 and 14. The rate of soil accumulation as shown is very fast relative to module lifetime. Therefore, some routine cleaning measures may be required in areas of severe soiling or some average performance decrement must be expected and accounted for in the solar-array economics. True long-term (10- to 20-yr) degradation effects due to soiling have not been quantified.

3. Cover Yellowing

Yellowing of some polymeric cover films and pottants has been observed in varying degrees both during laboratory accelerated testing and

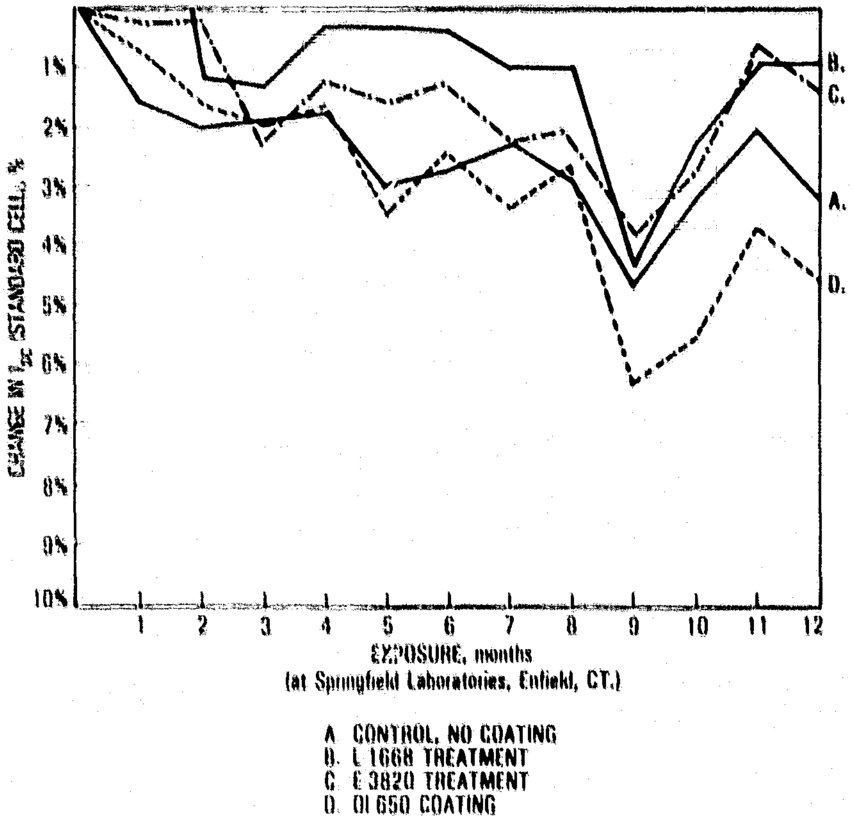

Figure 12. Change in Short-Circuit Current of Encapsulated PV Cells Due to Soiling in Outdoor Exposure (Sunadex Glass)

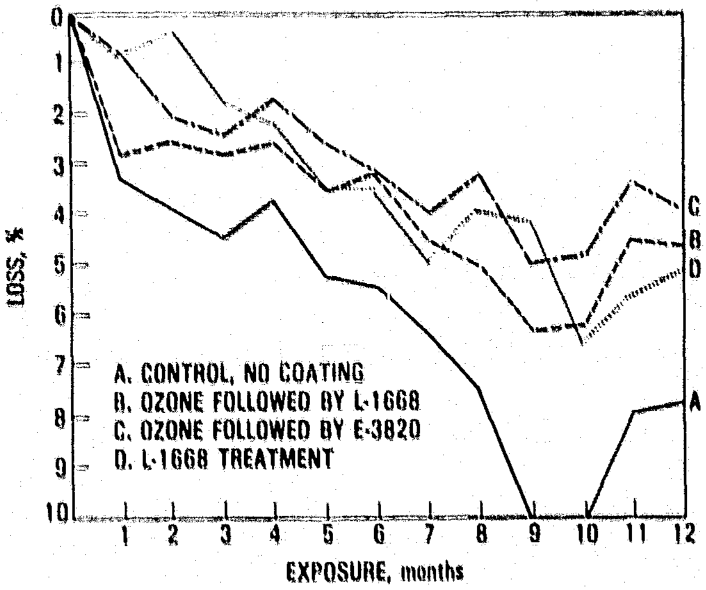

Figure 13. Change in Short-Circuit Current of Encapsulated PV Cells Due to Soiling in Outdoor Exposure; Acrylar Film (X-22417, 3M)

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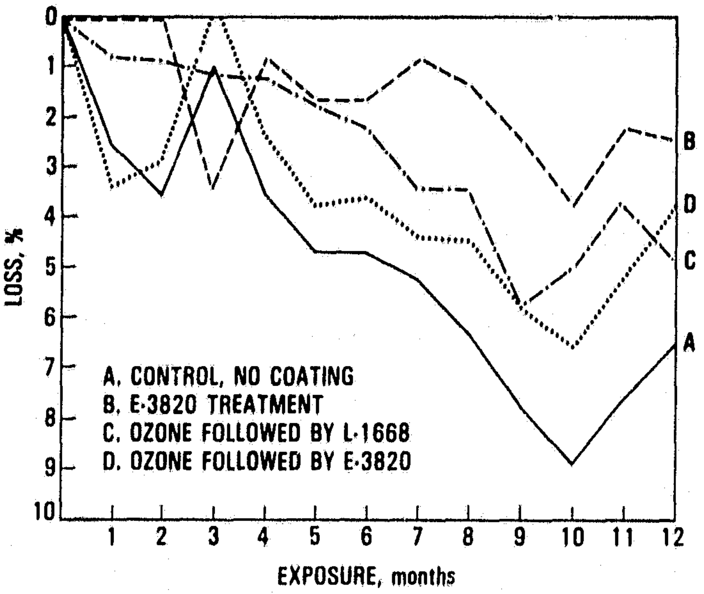

Figure 14. Change in Short-Circuit Current of Encapsulated PV Cells Due to Soiling in Outdoor Exposure; Tedlar Film (100BG30UT, Du Pont)

during normal field exposure of commercial and experimental modules. However, it must be noted that for most commercial PV modules exposed to normal application environments, the development of yellow or brown colors has been negligible or very localized within the module. Yellowing during field testing has been associated mainly with hot-spot cell heating or reactions with the edge-seal materials.

In the laboratory and in environmental test chambers capable of providing elevated temperature, high humidity, and intense ultraviolet radiation, the development of color and change in spectral transmission has been studied and is being documented and analyzed to assess the long-term outdoor optical stability of each of the candidate encapsulants along with changes in its electrical and mechanical characteristics.

The development of a yellow tint (absorption of blue) in the polymers covering solar cells may have only a small effect on module power. This is demonstrated by analyzing the effect of the spectral transmission curves of Figures 15 and 16 on solar-cell output. The difference in spectral transmission between a clear polymer and one with a definite yellow color due to high temperature and UV exposure is shown. Note that the major transmission differences are in the blue end of the spectrum around 400-500 nm. The spectral sensitivity of a typical silicon solar cell is shown in Figure 17. Its major power conversion wavelength range is between 500 nm and 1000 nm. The net effect of yellowing or optical degradation of a cover polymer is evaluated by an integration (as in Figure 18) of the polymer spectral transmission curves with the cell spectral sensitivity and the incident solar energy spectrum. The net loss in power transmission for the example shown is less than 7%, even though the loss in light transmission at 450 nm is greater than 40%. When

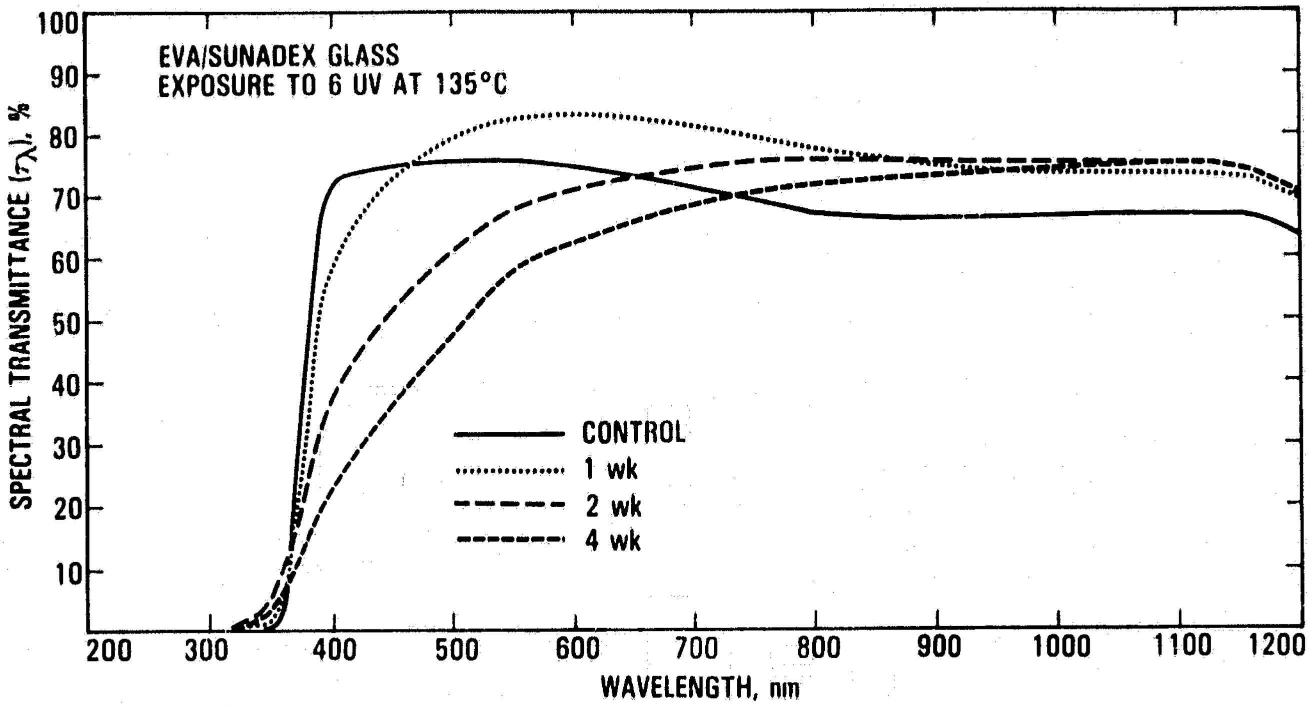

Figure 15. Change in Spectral Transmittance of Encapsulant EVA/Glass Configuration After Accelerated Exposure

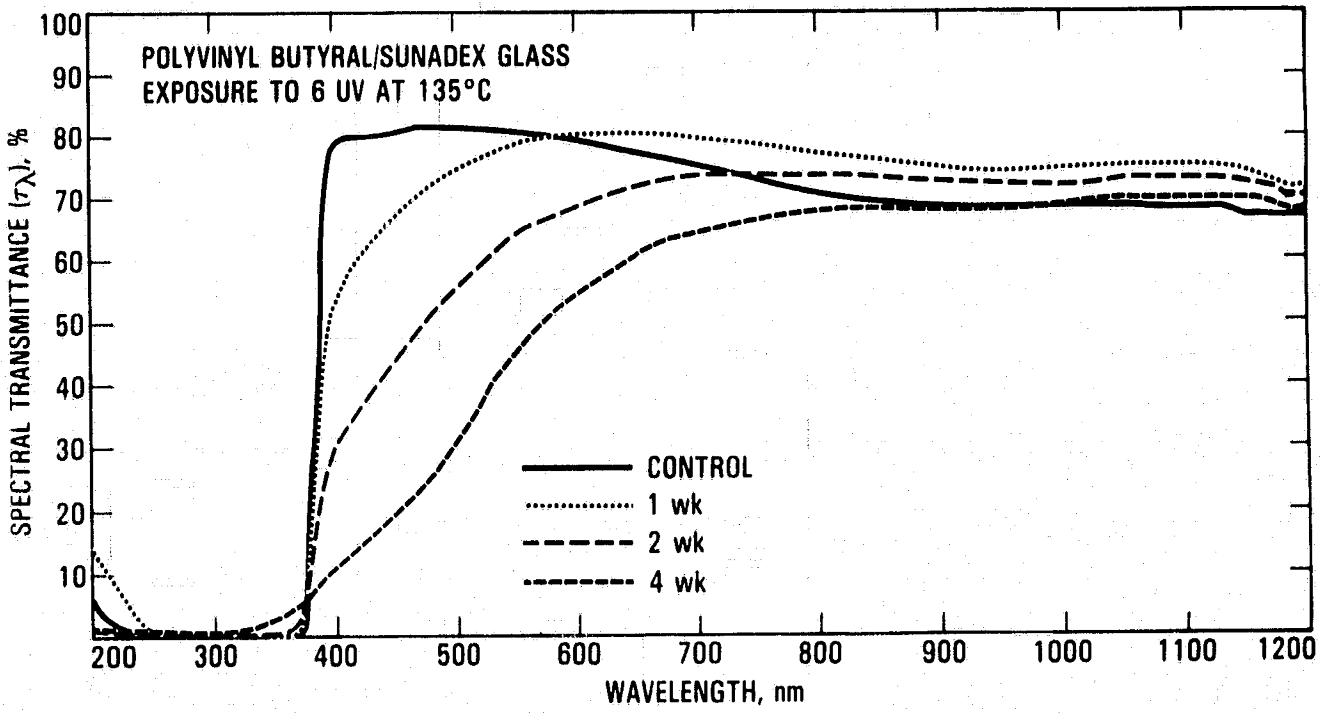

Figure 16. Change in Spectral Transmittance of Encapsulant PVB/Glass Configuration After Accelerated Exposure

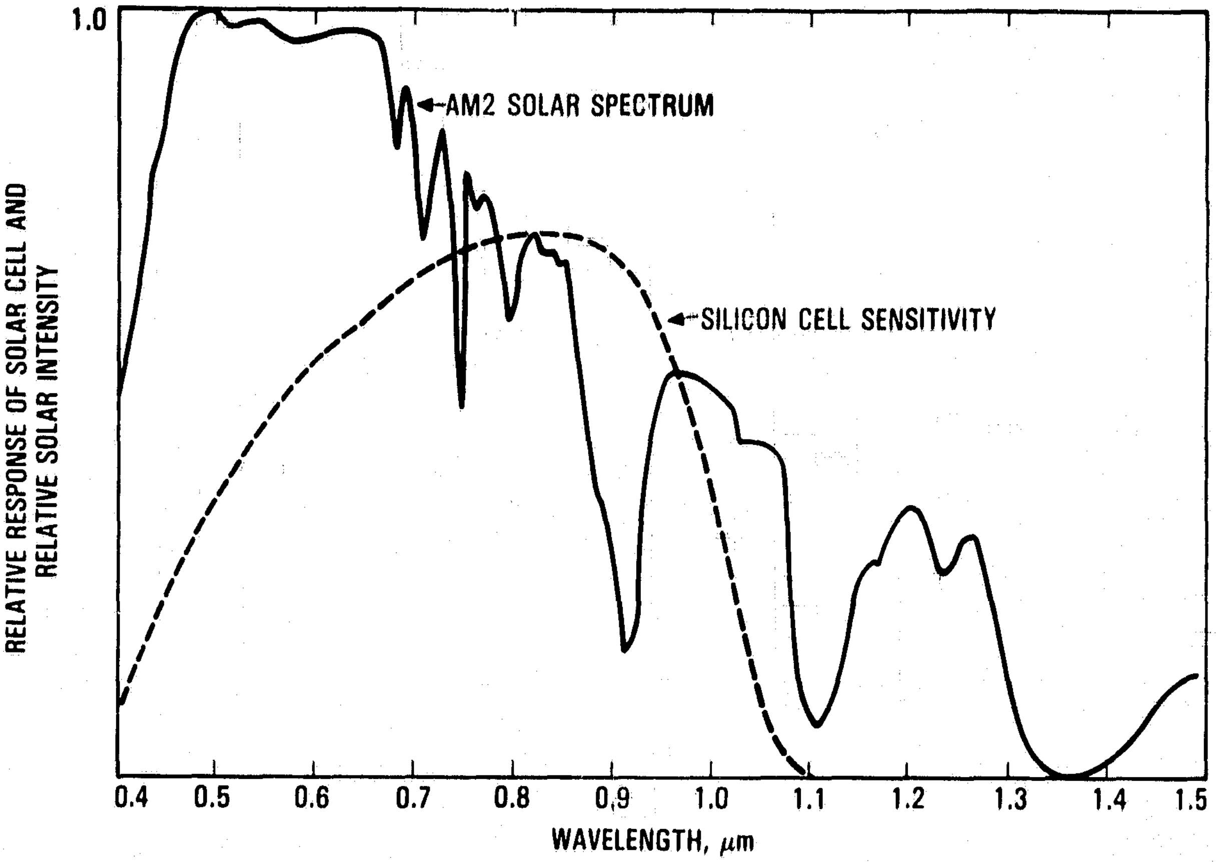

Figure 17. Spectral Response of Solar Cell and Spectrum of Solar Irradiance

the PVB polymer film specimen was further degraded for six weeks of photothermal oxidation at 135°C to a dark brown color, the spectral power output curve was as shown in Figure 19. The predicted power loss for a coupled PV cell would be 46%, while the optical transmission of the film at 500 nm was reduced from 81% to 13%, or a blue-region transmission loss of 84%. These data also indicate an increase in transmission of the longer wavelengths for some polymers.

Current experimental and analytical efforts are focused on correlating film optical degradation experimentally with PV-cell power losses, and developing correlations between accelerated laboratory photothermal degradation effects and long-term outdoor effects based on isolating the degrading mechanisms and understanding the related chemical reaction kinetics.

E. A GENERAL LIFE ASSESSMENT METHOD

It would be useful if an appropriate PV module qualification test or test series employing some degree of stress acceleration were available to assure the long-term (>20 yr) durability of solar array hardware under field conditions. To be useful for routine qualification of commercial hardware,

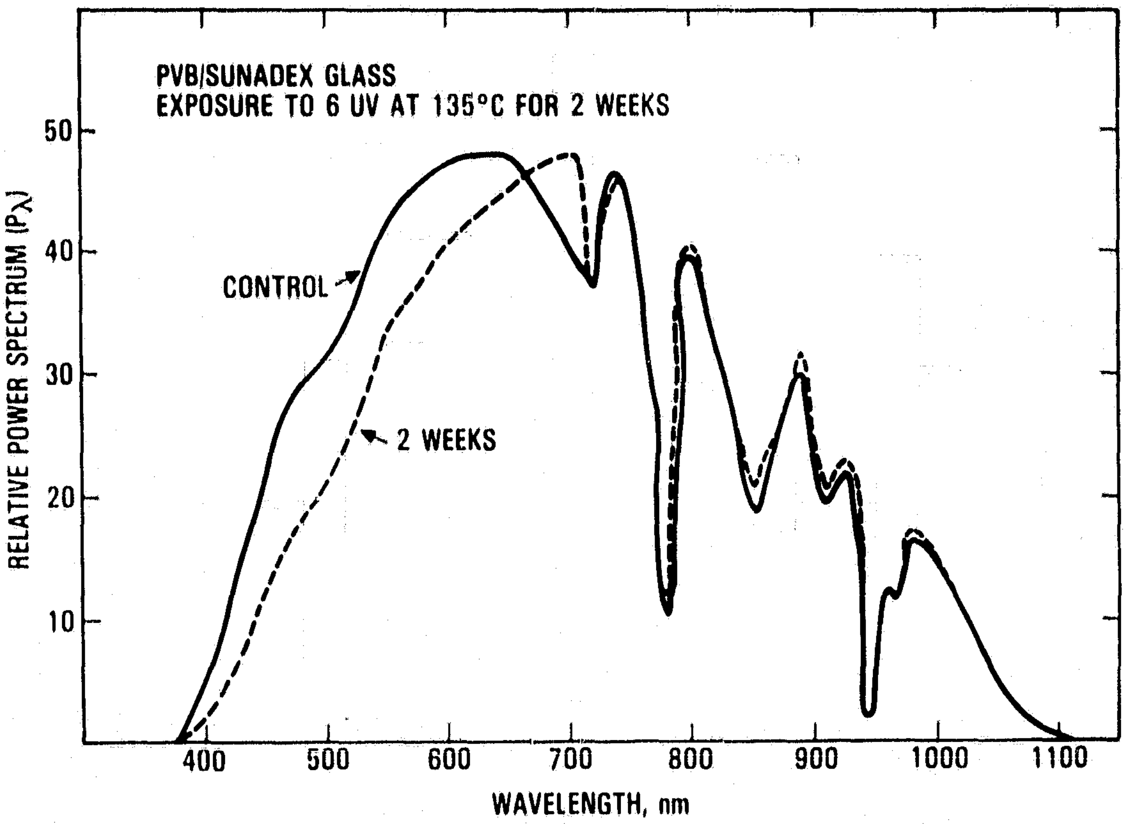

Figure 18. Predicted Spectral Power Output of Solar Cell Before and After 2 wk of Accelerated Exposure

the test results should be available in an exposure period of months (rather than years). Furthermore, such durability tests results must provide a distinction between long-term wear-out mechanisms and the random or infant-mortality types of damage.

A goal and focus of FSA efforts is to develop such tests and correlation relationships. At present, data and correlations are developing for several mechanisms that can be isolated and quantified. A brief summary of some of these individual damage mechanisms and their relationships to life assessment is presented below.

1. Interconnect Fatigue

The most complete example of analyzing and quantifying a module wear-out mode and developing a testing approach is the interconnect fatigue investigation by the Engineering Sciences Area of FSA as reported in Reference 13.

2. Optical Coupling

Another module degradation mechanism that may be amenable to long-term assessment by accelerated testing and analysis is optical

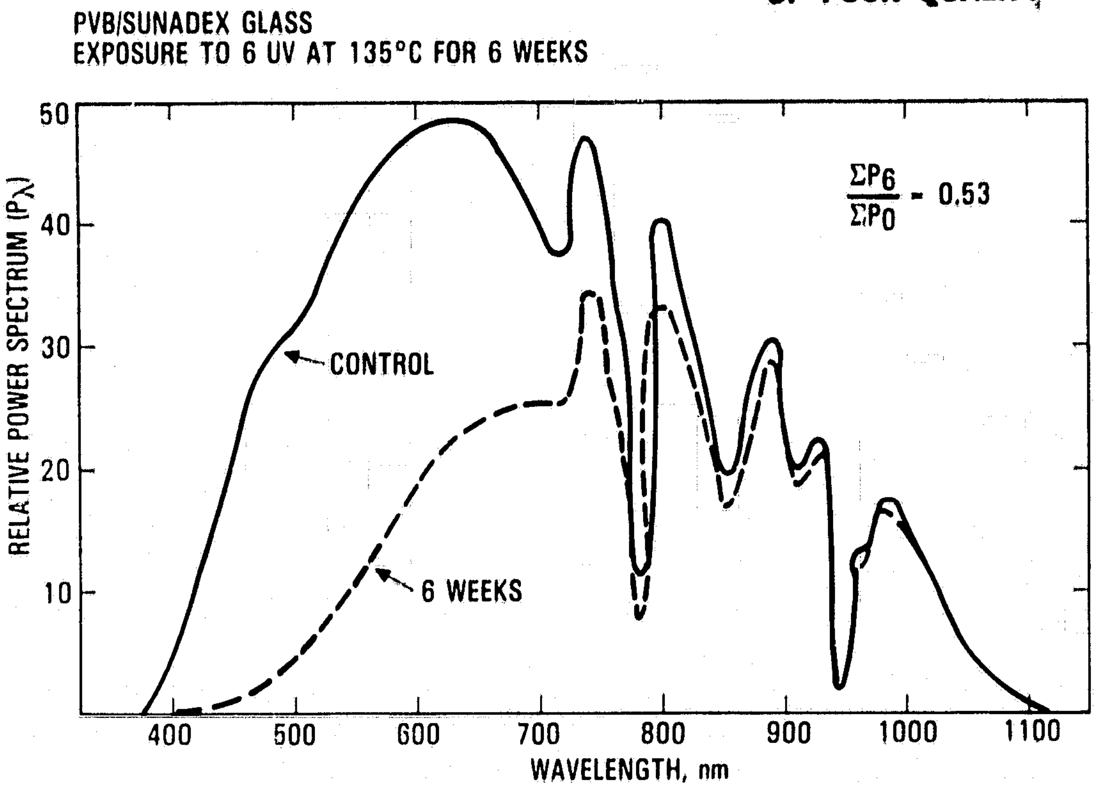

Figure 19. Predicted Spectral Power Output of Solar Cell Before and After 6 wk of Accelerated Exposure

degradation as described in the previous subsection. Data on polymer degradation are currently being accumulated and potential environmental correlation parameters are being developed. An expected result of these optical degradation studies is the formulation of a combined parameter LOAD variable that may include the cumulative incident UV radiation (in a selected bandwidth), the maximum PV cell temperature (or related temperature function) and atmospheric moisture (relative or absolute humidity). Degradation data, in the form of the exposure time for a PV cell or module to reach a specified performance decrement due to optical loss, would be plotted as a function of the combined LOAD parameter. It is expected that each type of module design or encapsulant material may yield a different correlation relationship and require a different set of accelerated-test conditions. Furthermore, in accelerated tests of complete modules there may well be simultaneous additive or competing damage mechanisms such as PV circuit or cell damage in addition to optical losses. Conceptually, the life-assessment correlation may appear as shown in Figure 20. Future module material component testing will, it is hoped, reveal which life-limiting damage mechanisms for each module design approach are the overriding ones, and allow valid extrapolation of the results of such accelerated tests and LOAD parameter correlations. References 37 and 38 describe some past and current work at Battelle Laboratories and at JPL in this area toward developing a combined LOAD parameter as a basis for life assessment using accelerated testing results.

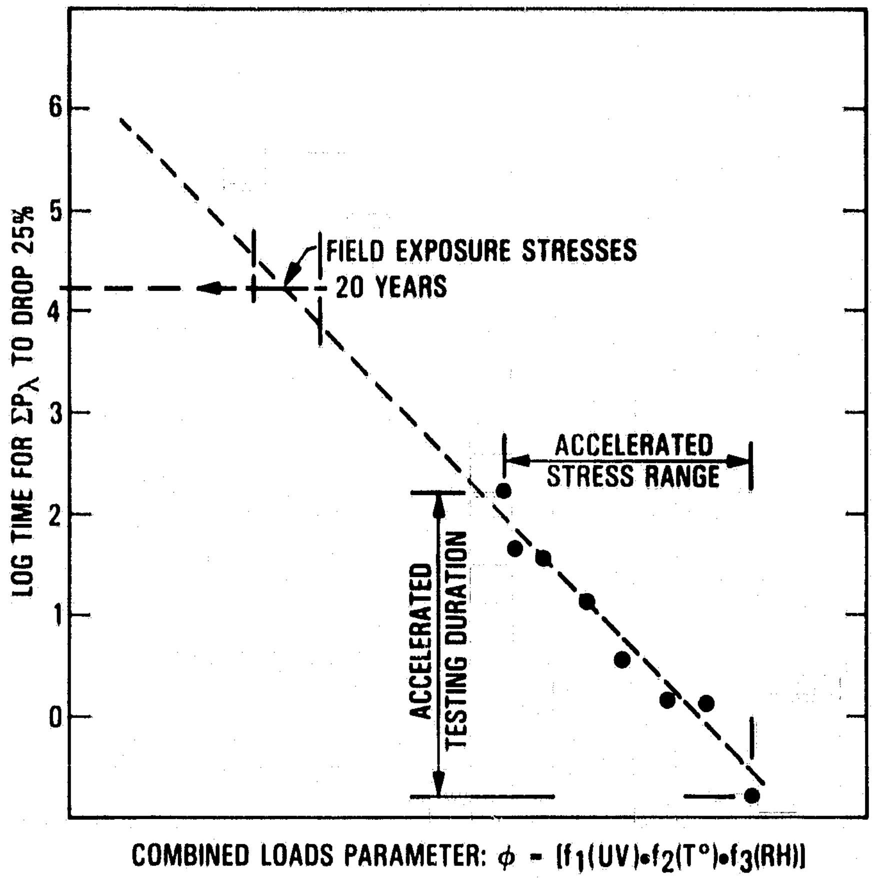

Figure 20. Form of DAMAGE Prediction Based on Accelerated Testing Correlation Parameter

3. Electrical Isolation

Electrical isolation or voltage breakdown failure depends on the combined effects of at least three independent factors, which make overall correlations and life assessment difficult. The first factor is the intrinsic dielectric strength of the material. This is usually a published value given in volts per mil. The second factor is the effect of flaws in thin-film materials such as Tedlar and polyester (Mylar) sheets. An example of the statistical nature of measured breakdown voltage for thin films and film laminates is shown in Figure 21, taken from Reference 25. A third factor is the effect of module configuration and fabrication flaws such as sharp projections and edges in the cell and interconnect geometry and possibly reduced insulation thicknesses caused by fabrication processes. Observations of voltage breakdown points in a module have almost invariably shown them to be at sharp edges or projections. The presence of bubbles in pottants seems to be a second-order effect.

All of these factors are present at the beginning of module life, and result in a wide variance of initial breakdown numbers (Reference 39). The limited data on the effect of aging on intrinsic dielectric strength and the effect of electrochemical reactions within an operating mdoule have been inconclusive. An increased effort by FSA is being applied to quantifying these potential wear-out mechanisms.

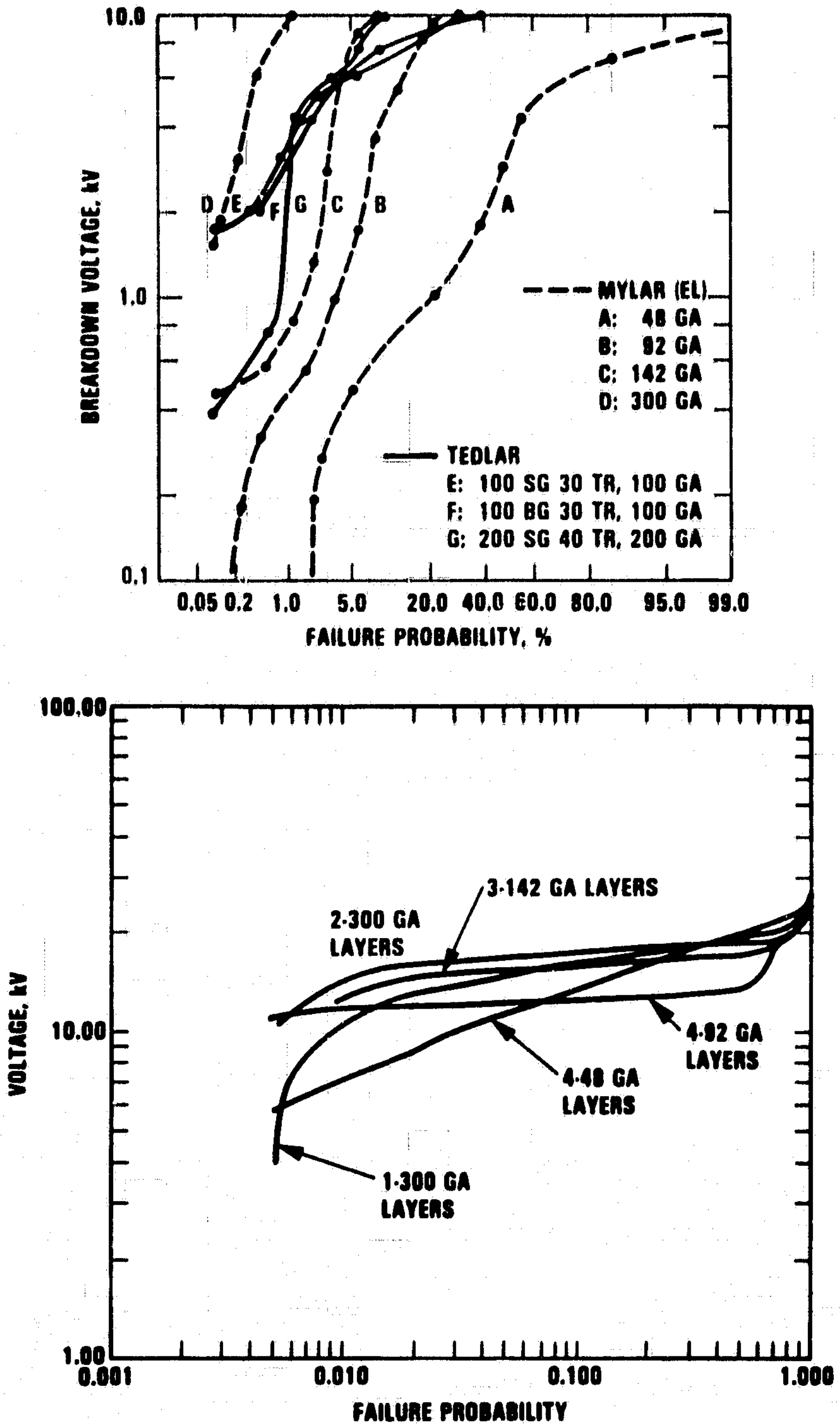

Figure 21. Dielectric Strength of Single and Multiple Layers of Polymer Films

Combined sequences of events leading to electrical degradation must also be evaluated. The aging effect on a polymer resulting in softening or shrinkage may cause the PV circuit elements to shift position and reduce insulating clearances and result in electrical shorting. (This has been observed).

Encapsulant glass-cover cracking or polymer sheet splitting may allow water intrusion, and this combined with the formation of an electrolyte and ion migration promoted by internal bias could lead to progressive reduced electrical isolation.

4. Degradation of Photovoltaic Solar Cells

An investigation of the reliability attributes and effect of accelerated stresses on terrestrial solar cells has been carried on at Clemson University since 1977. A summary and status report on their results is available in Reference 40. This program initially characterized the electrical and mechanical damage to unencapsulated solar cells from various manufacturers when exposed to accelerating levels of temperature, humidity, bias voltage, pressure, and temperature cycling. The initial result has been a ranking of the reliability or ruggedness of different types of cell metallization, and an identification of potential solar-cell damage mechanisms in severe environments. A limited number of encapsulated cells (in non-hermitic packages) exposed to the same environments experienced similiar degradation rates and damage (Figure 22).

The establishment of quantitative relationships between these accelerated testing results and the rate of potential cell degradation and performance loss in commercial modules deployed at various geographic sites is under development. A significant effort is focused on evaluating PV module testing in an environmental chamber at 85°C/85% relative humidity (RH) in order to establish relationships between the results of solar-cell testing at these severe conditions and the failure mechanisms observed in PV modules during field exposure (Reference 41).

5. Mechanical Properties of Polymers

Criteria for the required mechanical properties of polymeric materials used as pottants and cover films are being established and refined. An in-depth discussion of these requirements is presented in Reference 5. In general, the solar-cell pottant should be elastomeric, with a modulus of the magnitude of 1000 lb/in^2 or less and a thickness greater than 0.005 in. as shown in Figure 23, from Reference 5. This allows for the accommodation of bending strains and thermal-expansion differences between silicon solar cells and the module structural panel (substrate or superstrate). The common mechanical aging effects experienced by polymers are shrinkage, embrittlement, loss of elongation and material softening. During aging tests these effects may be monitored by weight loss and changes in the stress/strain data. Typical data for the aging effects of UV; temperature and oxygen access on candidate pottants from Reference 19 are shown in Figures 24 and 25.

The problem of predicting the quantitive consequences (DAMAGE) or module performance loss (FAILURE) associated with, for instance, a pottant modulus increase (CHANGE) can be appreciated by considering a possible sequence of degradation events involved as shown in Figure 26. If the predicted time rate of pottant modulus increase due to environmental aging over a 20-year period were to result in an excessive increase in solar-cell bending stress during extreme temperature swings or severe wind conditions, the quantitative

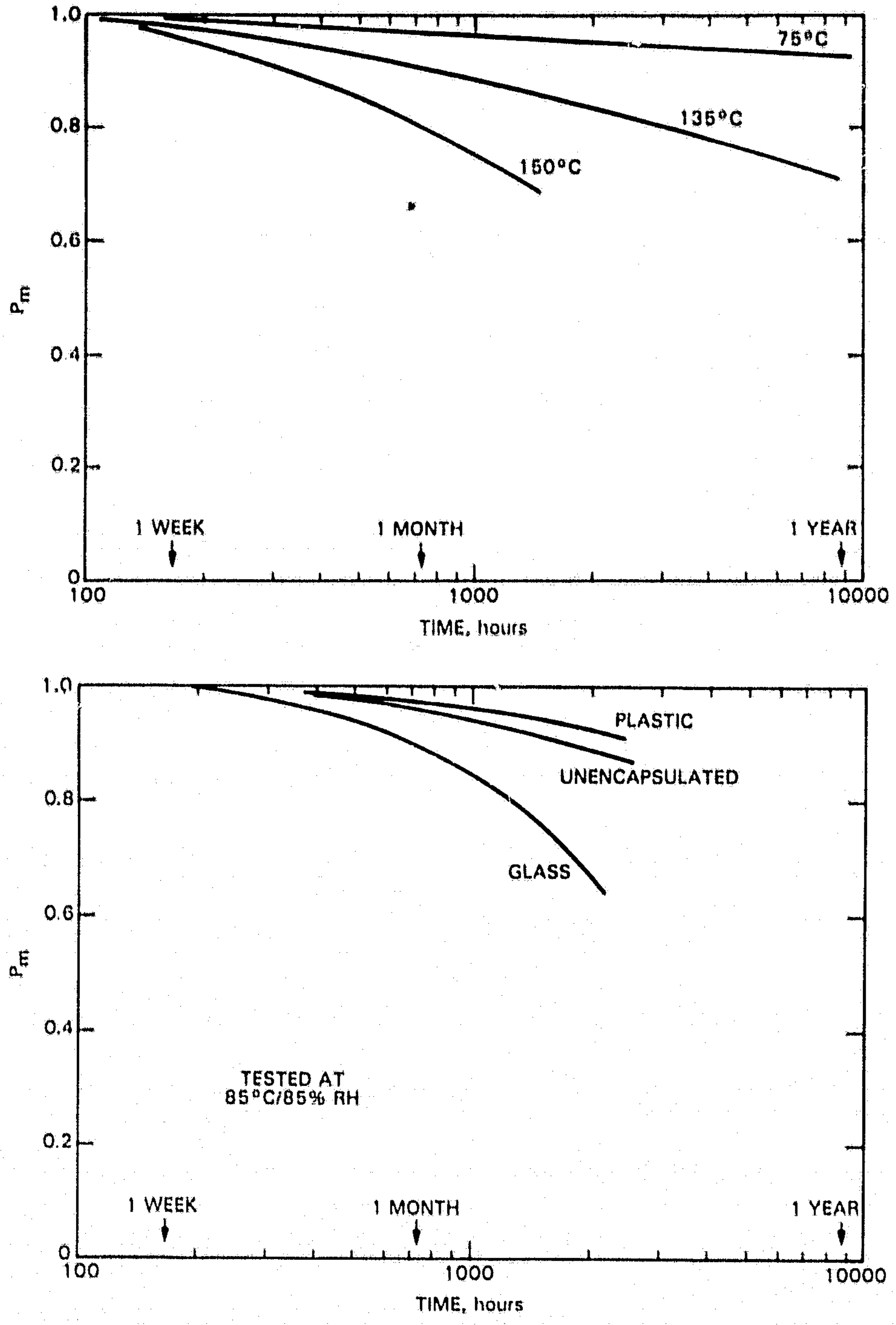

Figure 22. Effect of Temperature and Encapsulation on Solar-Cell Degradation Rate (Reference 40)

(DAMAGE) effect would only be an increased probability of cell cracking. The consequences of one or more cells cracking (DAMAGE) in a module or in an array field depends in turn on the array circuit design and on the fault-tolerant characteristics of each cell. The measurable consequences at the cell level may be an open circuit or may be negligible, depending on crack orientation,

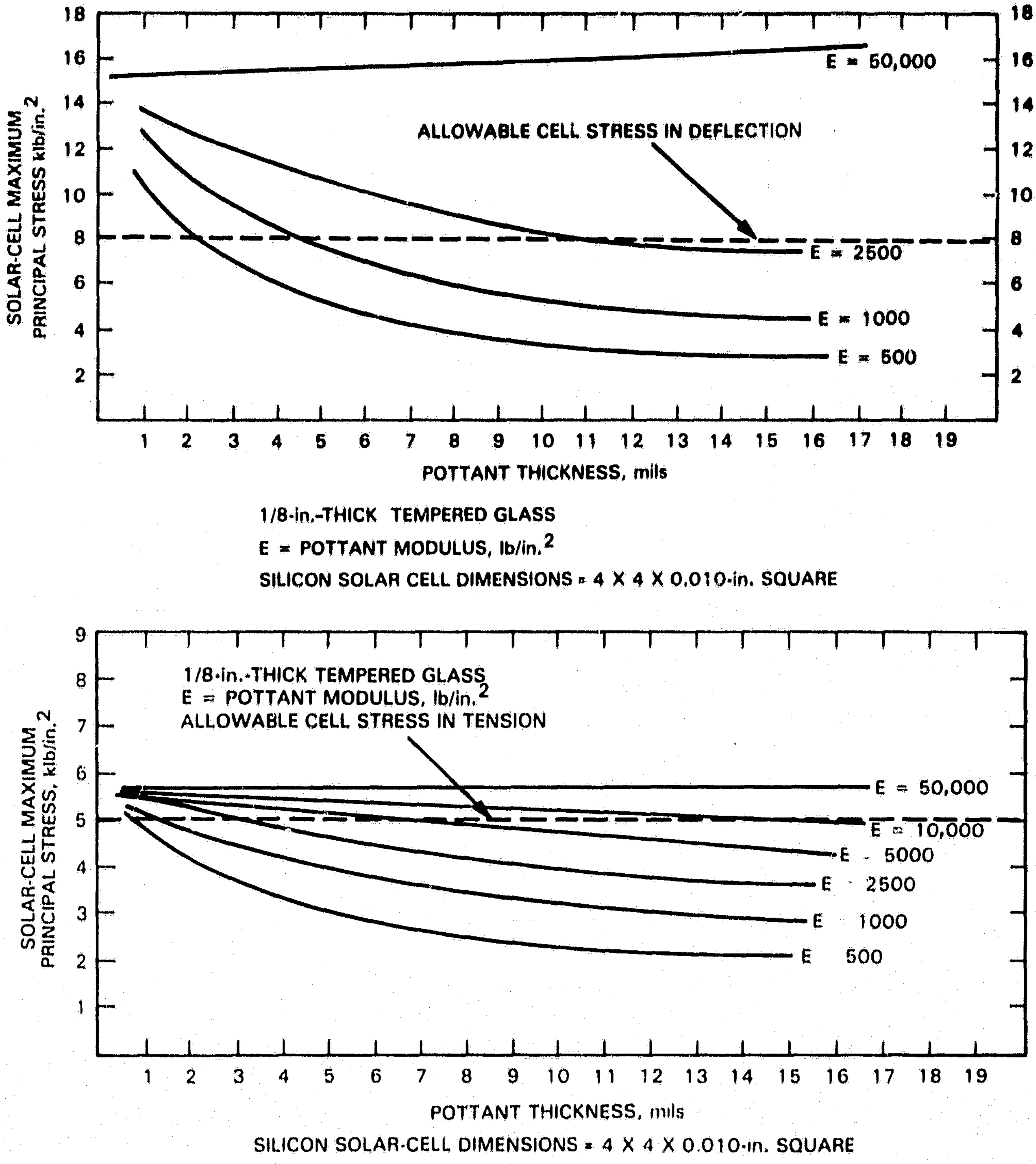

Figure 23. Effects of Pottant Modulus (E)

or a shunt may develop through the cell with time. Therefore, the development of a valid quantitative correlation between pottant modulus change and module failure rate is unlikely at this time.

A more realistic and conservative approach is to treat the excessive modulus (CHANGE) as a life-limiting property (DAMAGE) and select pottant

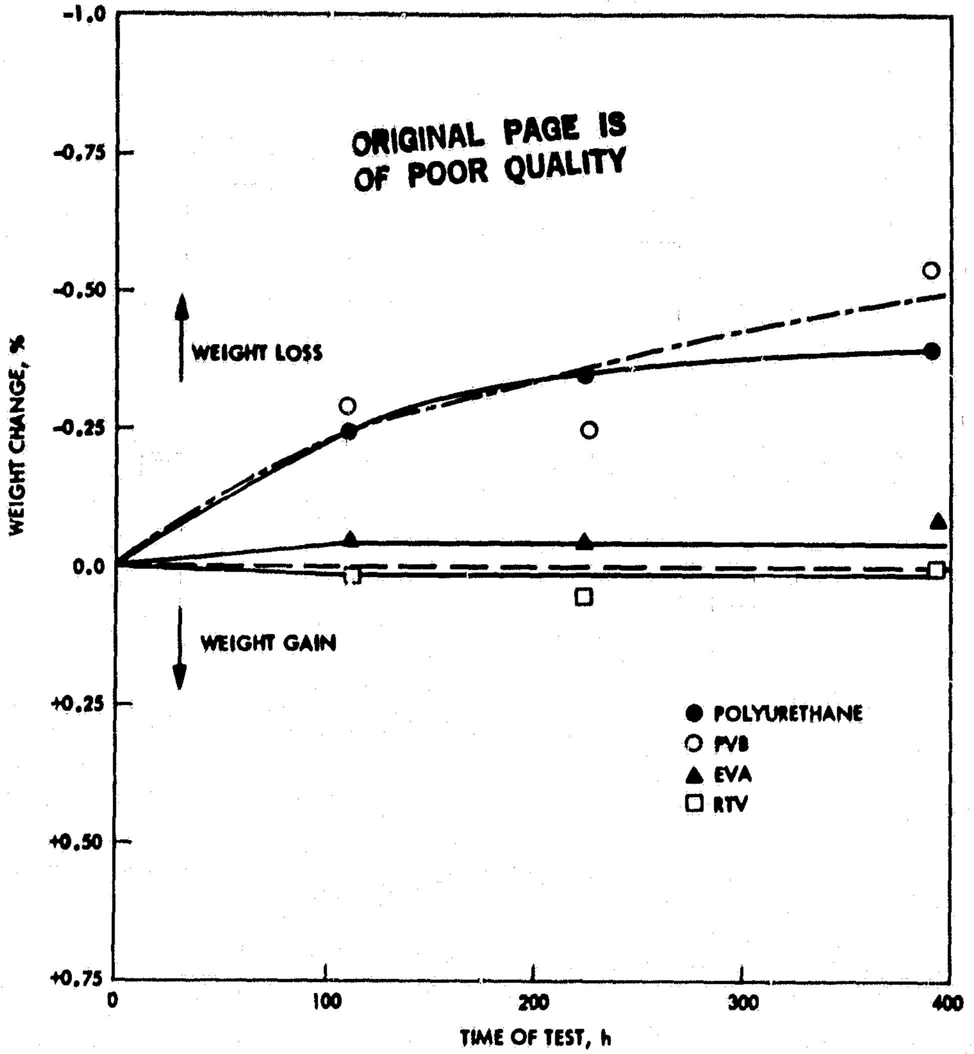

Figure 24. Percentage Weight Change of Pottant Materials as a Function of Photothermal Aging in Air at 6 suns and 70°C

materials and configurations that preclude such a modulus change and prevent the excessive cell stress from occurring.

This still leaves the task of developing the correlation between polymer mechanical property changes with exposure time and a combined parameter-variable applicable to field and accelerated-exposure conditions. This work is in process and the data base is being accumulated and analyzed.

A similar effort is being applied to the aging effects on other encapsulant properties. Polymeric cover films, whether on the front or back of a module, provide mechanical and abrasion protection and electrical isolation functions. Transparent front cover films also provide UV radiation filtering and maximum optical coupling with minimum soil retention and resistance to cleaning operations. The mechanical properties desired, therefore, are

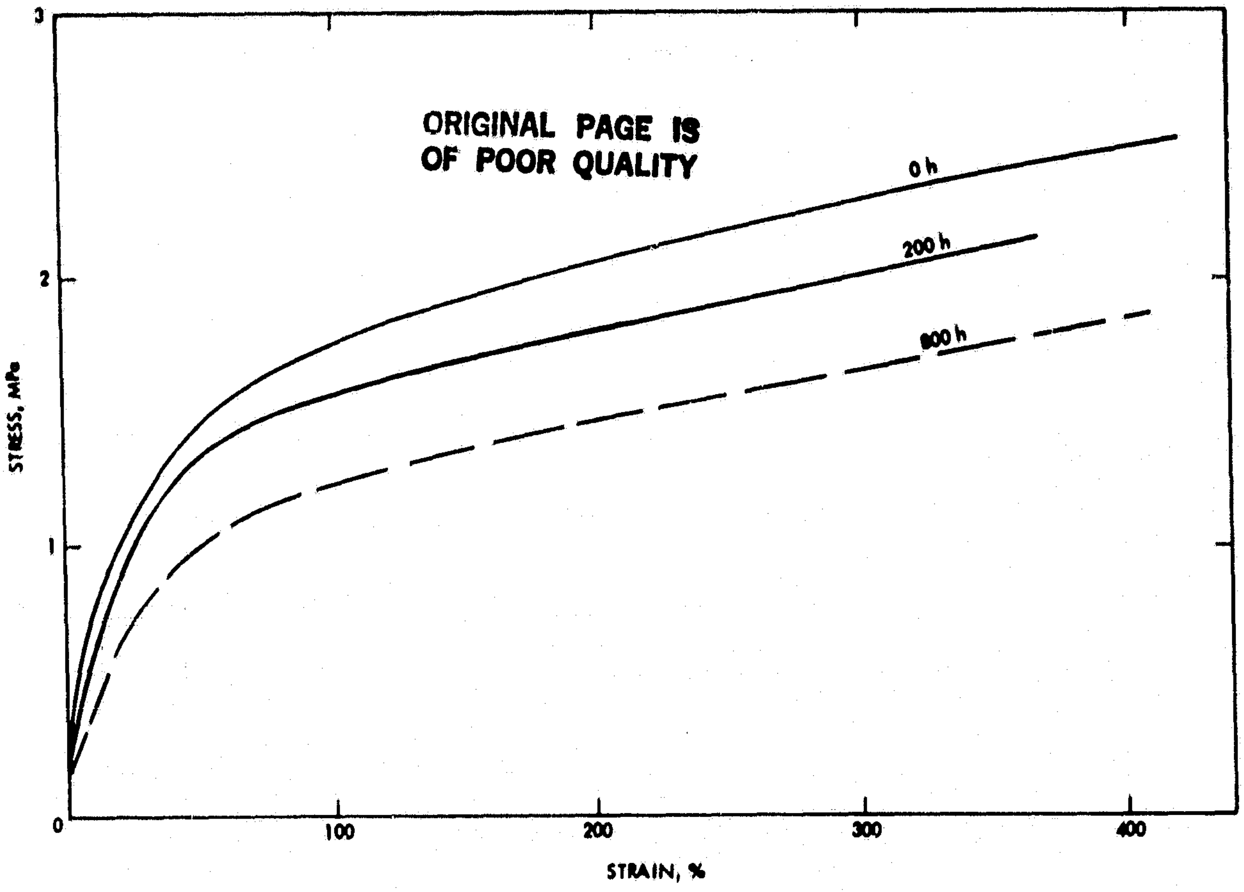

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Figure 25. Stress-Strain Curves of EVA Film A-9918 as a Function of Photothermal Aging at 6 suns and 105°C

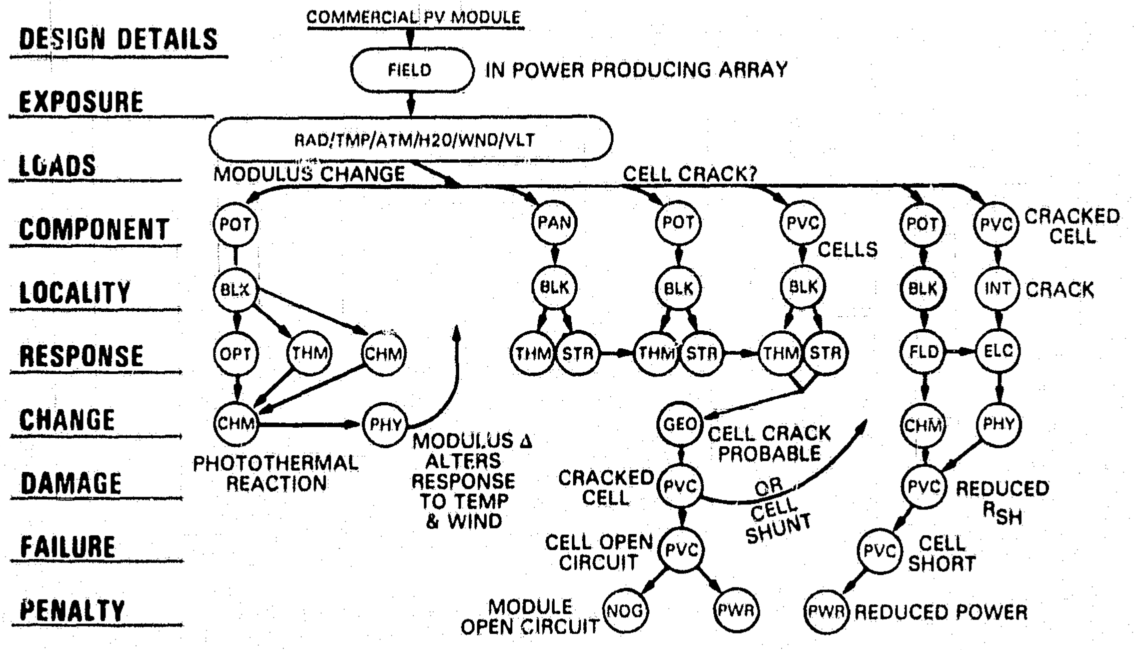

Figure 26. Durability Analysis of Effect of Pottant Modulus Increase

toughness and dimensional stability (minimum shrinkage). The goal of characterizing these materials is to set property-change limits that will assure their satisfactory performance for 20 years or more. Again, it is recognized that there may be no immediate performance consequences to such damage events as delamination or coverfilm cracking or splitting. However, such damage would give rise to the opportunity for water accumulation, followed by corrosion, followed by a degradation in PV circuit characteristics.

A conclusion drawn from the foregoing discussion may be that the module design criteria for achieving 20-year-or-greater service life may be related as much to limiting visible DAMAGE as to limiting the calculated module performance PENALTY.

SECTION IV

CONCLUSIONS

1. A failure analysis matrix has been formulated as an organizing aid for unifying and integrating all data and relationships useful in assessing the life potential of PV modules.

2. Specific accelerated testing methods and correlation relationships have been developed and are being developed to predict failure probability and to assess specific failure modes that must be prevented to ensure a 20-year life. These degradation relationships include interconnect fatigue, hail damage, wind damage, pottant yellowing, electrical isolation and soiling.

3. Other potential module failure modes involving cell cracking, corrosion and material degradation, which involve a sequence or combination of material changes and damage events, are presently less amenable to quantification of module performance loss as a function of time.

4. For module life assessment and design analysis, the conservative and most practical approach at present is to design for DAMAGE control or prevention, even though the corresponding potential immediate module performance loss (PENALTY) may be negligible, as indicated by available field-testing or accelerated-testing results.

5. The approach recommended for relating material stability data to photovoltaic module life is to use the degree of DAMAGE to (1) optical coupling, (2) encapsulant package integrity, (3) PV circuit integrity or (4) electrical isolation as the quantitative criterion for assessing module potential service life rather than simply using module power loss.

REFERENCES

1. Hoffman, A.R., and Maag, C.R., "Airborne Particulate Soiling of Terrestrial Photovoltaic Modules and Cover Materials," Proceedings of the Institute of Environmental Sciences, Philadelphia, Pennsylvania, May 11-14, 1980, Institute of Environmental Sciences, Mt. Prospect, Illinois, 1980.

2. Hoffman, A.R., and Maag, C.R., Photovoltaic Module Soiling Studies, May 1978 to October 1980, JPL Publication 80-87, JPL Document No. 5101-131, DOE/JPL-1012-49, Jet Propulsion Laboratory, Pasadena, California, November 1, 1980.

3. Cuddihy, E.F., "Theoretical Considerations of Soil Retention," Solar Energy Materials, Vol. 3, pp. 21-33, 1980.

4. Investigations of Test Methods, Material Properties, and Processes for Solar-Cell Encapsulants, Annual Report, Springborn Laboratories, Inc., Enfield, Connecticut, and DOE/JPL 954527-82-23, Jet Propulsion Laboratory, Pasadena, California, July 1982.

5. Cuddihy, E., et al, Photovoltaic Module Encapsulation Design and Materials Selection: Volume I, JPL Publication 81-102, JPL Document No. 5101-177, DOE/JPL-1012-60, Jet Propulsion Laboratory, Pasadena, California, June 1, 1982.

6. Terrestrial Service Environments for Selected Geographic Locations, ERDA/JPL-954328-76/5, Battelle Columbus Laboratories, Columbus, Ohio, June 24, 1976.

7. Gonzalez, C.C., Environmental Hail Model for Assessing Risk to Solar Collectors, JPL Internal Document No. 5101-45, Jet Propulsion Laboratory, Pasadena, California, December 1977.

8. Moore, D.M., and Wilson, A.H., Photovoltaic Solar Panel Resistance to Simulated Hail, JPL Document No. 5101-62, DOE/JPL-1012-78/6, Jet Propulsion Laboratory, Pasadena, California, October 15, 1978.

9. Bouquet, F.L., "Glass as Encapsulation for Low-Cost Photovoltaic Solar Arrays," J. Solar Energy Eng., Vol. 103, p. 221, August 1981.

10. Wind Loads on Flat-Plate Photovoltaic Array Fields, DOE/JPL 954833-81/3, Boeing Engineering and Construction Co., Seattle, Washington, April 1981.

11. Wen, L., An Investigation of the Effect of Wind Cooling on Photovoltaic Arrays, JPL Publication 82-28, JPL Document No. 5101-201, DOE/JPL-1012-69, Jet Propulsion Laboratory, Pasadena, California, March 1982.

12. Mon, G.R., Moore, D.M., and Ross, R.G., "Solar-Cell Interconnect Design for Terrestrial Photovoltaic Modules," presented at the 4th ASME Solar Division Annual Tech. Conf., Albuquerque, New Mexico, April 26-30, 1982.

13. Mon, G.R., Moore, D.M., and Ross, R.G., Jr., Interconnect Fatigue Design for Terrestrial Photovoltaic Modules, JPL Publication 81-111, JPL Document No. 5101-173, DOE/JPL-1012-62, Jet Propulsion Laboratory, Pasadena, California, March 1982.

14. Gupta, A., Photodegradation of Polymeric Encapsulants of Solar Cell Modules, JPL Internal Document No. 5101-77, Jet Propulsion Laboratory, Pasadena, California, August 1978.

15. Gupta, A., and Di Stefano, S., "Photocatalytic Degradation of a Crosslinked Ethylene/Vinyl Acetate (EVA) Elastomer," Polymer Preprints, 21, 178, 1980.

16. Gupta, A., Effect of Photodegradation on Chemical Structure and Surface Characteristics of Silicon Pottants Used in Solar Cell Modules, JPL Internal Document No. 5101-79, Jet Propulsion Laboratory, Pasadena, California, August 1978.

17. Liang, R., Yavrouian, A., and Gupta, A., "Development of a Weatherable Acrylic Elastomer for Solar Cell Encapsulation," Proceedings of the 158th Meeting of the Electrochemical Society, Hollywood, Florida, October 1980.

18. Guillet, J., Modelling of Photoxidation of Pottants for Flat-Plate Solar Array Applications and Predicitng Useful Lifetimes of Such Polymeric Materials, Interim Report, University of Toronto, Toronto, Canada, 1981.

19. Liang, R., et al, Photothermal Characterization of Encapsulant Materials for Photovoltaic Modules, JPL Publication 82-32, JPL Document No. 5101-210, DOE/JPL-1012-72, Jet Propulsion Laboratory, Pasadena, California, June 1, 1982.

20. Chen, C.P., Fracture Strength of Silicon Solar Cells, JPL Publication 79-102, JPL Document No. 5101-137, DOE/JPL-1012-32, Jet Propulsion Laboratory, Pasadena, California, October 15, 1979.

21. Ross, R.G., Jr., "Photovoltaic Module and Array Reliability," Proceedings of the 15th Photovoltaic Specialists Conference, Orlando, Florida, May 1981.

22. Gonzalez, C.C., and Weaver, R., "Circuit Design Considerations for Photovoltaic Modules and Systems," Proceedings of the 14th IEEE Photovoltaic Specialists Conference, San Diego, California, January 1980.

23. Chen, C.P., Effect of Loading Rates on the Strength of Silicon Wafers, JPL Internal Document No. 5101-190, Jet Propulsion Laboratory, Pasadena, California, December 1980.

24. Mon, G.R., "Defect Design of Insulation Systems for Photovoltaic Modules," presented at 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981.

25. Progress Report 19 and Proceedings of the 19th Project Integration Meeting, JPL Publication 82-11, JPL Document No. 5101-194, DOE/JPL-1012-67, Jet Propulsion Laboratory, Pasadena, California, July-November 1981.

26. Ross, R.G., "Design Techniques for Flat-Plate Photovoltaic Arrays," presented at the 15th IEEE Photovoltaic Specialist Conference, Orlando, Florida, May 12-15, 1981.

27. Ross, R.G., Jr., "Flat-Plate Photovoltaic Array Design Optimization," Proceedings of the 14th IEEE Photovoltaic Specialists Conference, San Diego, California, January 1980, P. 1126.

28. Weaver, R., "Flat-Plate Photovoltaic Array Simulation and Design Analysis," Proceedings of the Systems Simulation and Economic Analysis Conference, SERI/TP-351-431, January 1980, pp. 105-112.

29. Jaffe, P., LSA Field Test Annual Report, August 1979 to August 1980, JPL Publication 81-12, JPL Document No. 5101-166, Jet Propulsion Laboratory, Pasadena, California, December 1980.

30. Trenchard, S.E., Testing of Solar Photovoltaic Arrays for Utilization on Marine Aids to Navigation, U.S. Coast Guard Report No. CG-D-10-81, U.S. Coast Guard Research and Development Center, Avery Point, Groton, Connecticut, November 1980.

31. Jaffe, P., Weaver, R.W., and Lee, R.E., FSA Field Test Annual Report August 1980-August 1981, JPL Publication 81-99, DOE/JPL-1012-59, JPL Document No. 5101-197, Jet Propulsion Laboratory, Pasadena, California, December 1981.

32. Griffith, J.A., Rathod, M.S., and Paslaski, J., "Some Tests of Flat Plate Photovoltaic Module Cell Temperatures in Simulated Field Conditions," presented at 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981.

33. Gupta, A., et al, "Photochemical Processes in Polymeric Systems. 2. Photochemistry of a Polycarbonate of Bisphenol A in Solution and in the Solid Phase," Macromolecules, Vol. 13, p. 262, American Chemical Society, Washington, D.C., March-April 1980.

34. Block V Solar Cell Module Design and Test Specification for Residential Applications--1981, JPL Internal Document No. 5101-161, Jet Propulsion Laboratory, Pasadena, California, February 20, 1981.

35. Flat-Plate Photovoltaic Module and Array Circuit Design Optimization Workshop Proceedings--May 19-20, 1980, JPL Internal Document No. 5101-170, Jet Propulsion Laboratory, Pasadena, California.

36. Frickland, P.O., and Repar, J., Experimental Evaluation of the Battelle Accelerated Test Design, JPL Publication 82-52, JPL Document No. 5101-211, DOE/JPL-1012-73, Jet Propulsion Laboratory, Pasadena, California, April 1980.

37. Gaines, G.B., et al, *Development of an Accelerated Test Design for Predicting the Service Life of the Solar Array* at Mead, Nebraska, Final Report, DOE/JPL-954328-79/13, Battelle Columbus Laboratories, Columbus, Ohio, June 1979.

38. *Progress Report 20 and Proceedings of the 20th Project Integration Meeting*, JPL Publication 82-48, JPL Document No. 5101-209, DOE/JPL-1012-71, Jet Propulsion Laboratory, Pasadena, California, November 1981-April 1981.

39. Garcia, A., and Minning, C., *Phase II Program Results Periodic Report Supplement on the Design, Analysis and Test Verification of Advanced Encapsulation Systems for Period Ending 1 October 1981*, DOE/JPL-955567-82/8, Spectrolab, Inc., Sylmar, California, June 1982.

40. Lathrop, J.W., *Investigation of Reliability Attributes and Accelerated Stress Factors on Terrestrial Solar Cells*, 1981 Summary Report, DOE/JPL-954929-82/9, Clemson University, Clemson, South Carolina, June 1982.

41. Otth, D.H., and Ross, R.G. Jr., "Assessing Photovoltaic Module Degradation and Lifetime From Long-Term Environment Tests," prepared for presentation at the annual meeting of the Institute of Environmental Sciences, April 18, 1983, in Los Angeles, California.

Appendix A

Failure Analysis Matrix Symbol Definition

Appendix A

FAILURE ANALYSIS MATRIX SYMBOL DEFINITION

To outline specific testing and failure analysis activities, either past or future, in such a way as to assess their scope and to provide a basis for comparisons and identification of limitations, the chart of Figure A-1 has been rearranged in the format of Figure A-2. There is a one-to-one correspondence between the words and the three-letter abbreviations in the two charts. Expanded definitions of the abbreviations are listed on the following page.

For developing a test or analysis flow chart, the format provides for describing the test hardware or material alongside DESIGN DETAILS. Inasmuch as any manufacturing flaws or discrepancies (if known) are part of the initial state of the hardware, they are included in DESIGN DETAILS.

The chart of Figure A-2 is used mainly to define terms and designate the parameter classifications. To outline a specific test and analysis sequence, a blank chart as shown in Figure A-3 may be used to plot the specific parameters and relationships with appropriate boxes and arrows. The example described in the main text is shown as Figure A-4.

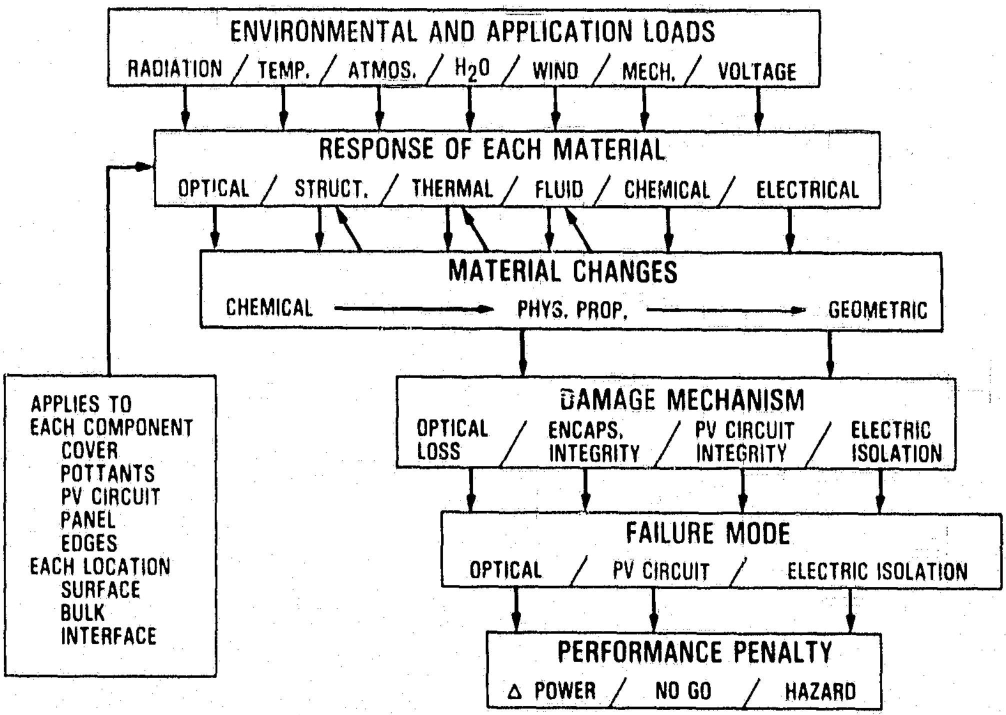

Figure A-1. PV Module Failure-Analysis Matrix

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DESIGN DETAILS									CONF, MTL & FLAWS
EXPOSURE	QUAL		FIELD	ACCEL / TIME					TEST CONDITIONS
LOADS	RAD	TMP	ATM	H2O	WND	MEC	VLT		INTENSITY/TIME
COMPONENT	COV	POT	PAN	EDG	PVC				OR MATERIALS
LOCALITY	SRF	BLK	INT						WHICH OR WHERE
RESPONSE	OPT	STR	THM	FLD	CHM	ELC			QUANTITATIVE
CHANGE	CHM	PHY	GEO						MEASURABLE/VISIBLE
DAMAGE	OPT	ENC	PVC	ISO					INTEGRITY VIOLATED
FAILURE	OPT	PVC	ISO						OPERATIONAL
PENALTY	PWR	NOG	HZD						VALUE LOSS

Figure A-2. Durability-Analysis Categories

DESIGN DETAILS								
EXPOSURE								
LOADS								
COMPONENT								
LOCALITY								
RESPONSE								
CHANGE								
DAMAGE								
FAILURE								
PENALTY								

Figure A-3. Durability-Analysis Plan Outline

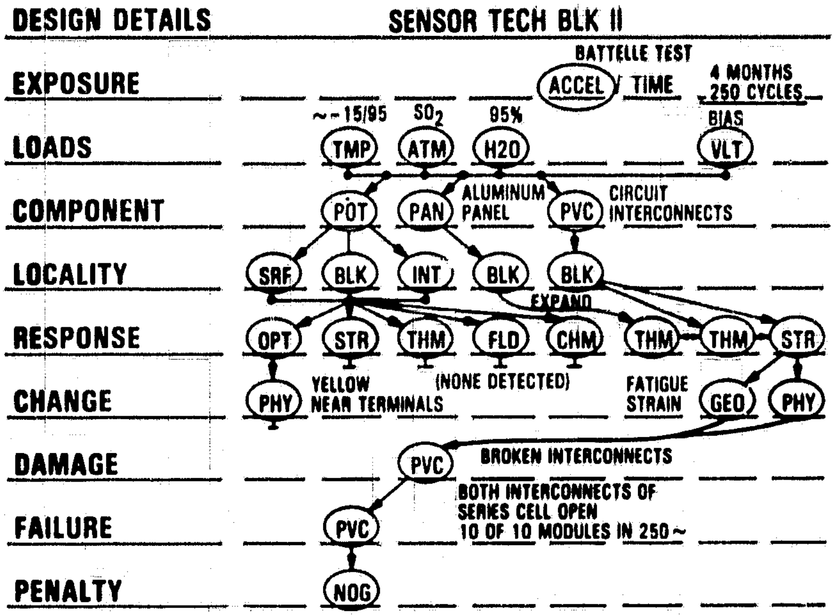

Figure A-4. Durability-Analysis Example Assessing Accelerated Test Program Results

MATRIX ABBREVIATION KEY

EXPOSURE

QUAL = JPL qualification tests
FIELD = Normal field exposure environments
ACCEL = Artificial controlled loads applied
TIME = Time period or cycles involved

LOADS

RAD = Spectral radiation intensities
TMP = Environmental temperature
ATM = Atmospheric constituents (except moisture)
H2O = Moisture in all its forms: humidity, rain, hail, etc.
WND = Wind specification
MEC = All mechanical/physical loads applied to the module by handling, mounting, earthquake, etc.
VLT = Voltage or current bias present that may effect operation or response

COMPONENT

COV = Covers (glass, polymers, foils) on front or back of module that protect the softer pottant or the structural panel
POT = The low-modulus pottant material encapsulating the PV circuit and solar cells
PAN = The structural panel, which may be either a transparent superstrate or low-cost substrate
EDG = All module edge-treatment seals, gaskets, and framing
PVC = Photovoltaic circuit components: cells, metallization, interconnects, bus bars, terminals, diodes

LOCALITY

SRF = Surface
BLK = Bulk
INT = Interface

RESPONSE

OPT = Optical
STR = Structural/mechanical
THM = Thermal/temperature
FLD = Fluid: liquid, vapor or gaseous, transmission absorption, etc.
CHM = Chemical reactions or changes (reversible or permanent) including change of state
ELC = Resulting voltages and currents

CHANGE

CHM = Chemical structure change
PHY = Physical property change (optical, thermal, structural, electrical, etc.)
GEO = Visible change in geometry or configuration

DAMAGE

OPT = Optical transmission loss in solar cell response range
ENC = Encapsulant package integrity
PVC = PV circuit integrity
ISO = Electrical isolation

FAILURE

OPT = Optical transmission loss in solar cell response range
PVC = PV circuit power loss
ISO = Electrical isolation breakdown

PENALTY

PWR = Quantitative loss of power
NOG = No-go, inoperative module due to short or open circuit
HZD = Safety hazard requiring corrections